# NOνA Update (part one) :

1. **TASD** (Totally Active Scintillator Detector)
2. **Compare TASD, Baseline, RPC**
3. **R&D status and plans**

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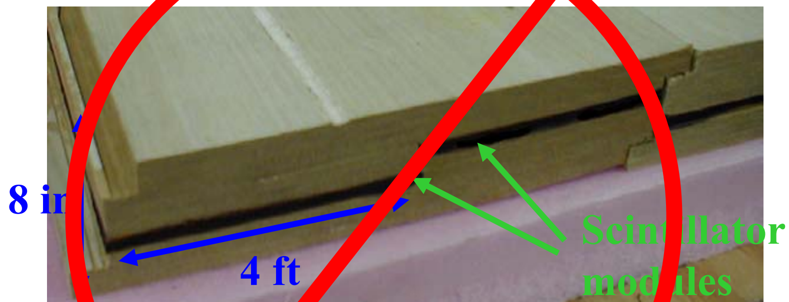
June 20, 2004

@ Fermilab PAC Meeting

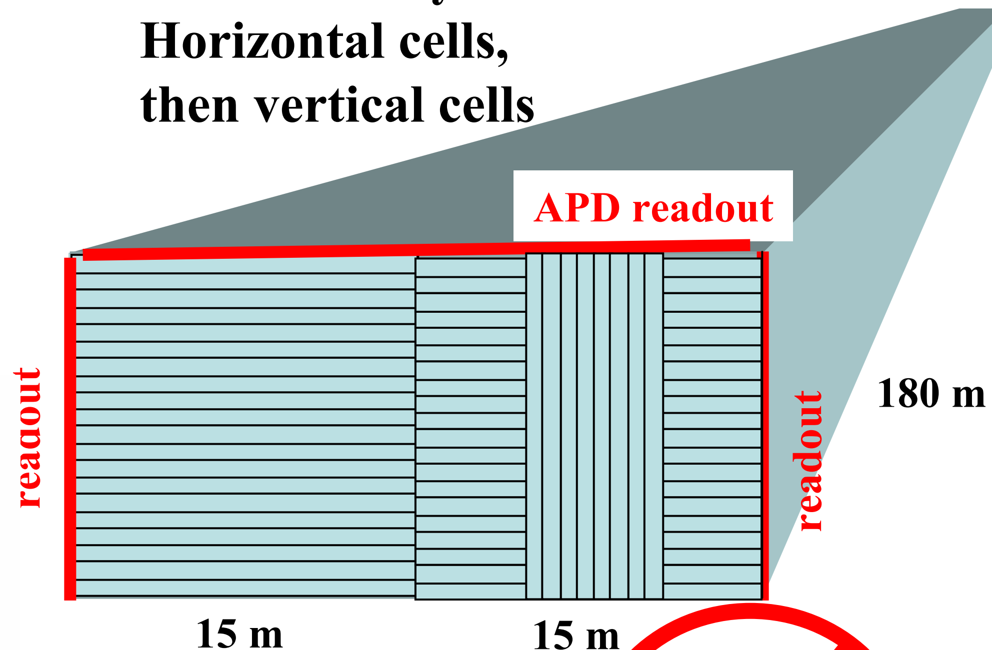
# Baseline Design: 50 kTons

**(14% scintillator)**

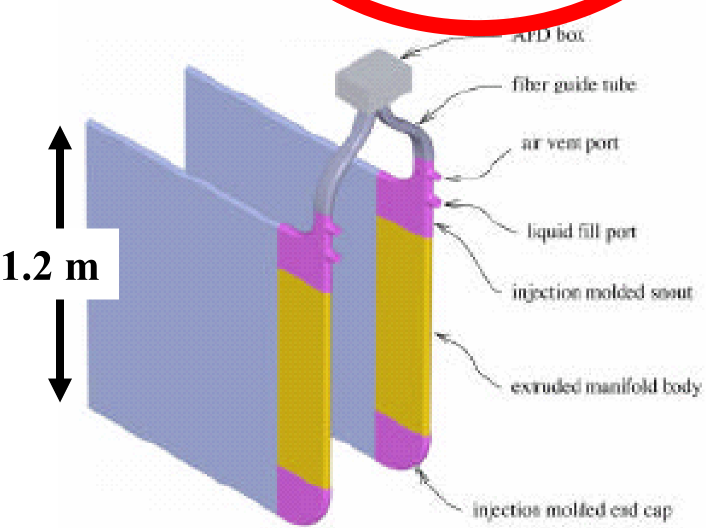



**Particle board with slots**
**For liquid scintillator modules**

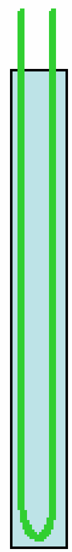
**Successive layers have**
**Horizontal cells,**
**then vertical cells**




**APD readout**
**on 3 edges**



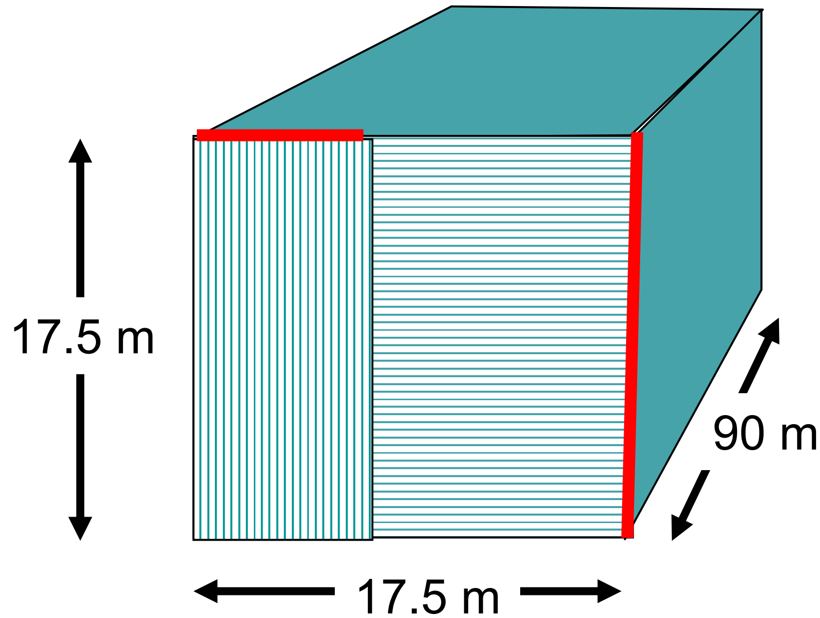

**1.2 m wide, 15 m long**
**PVC extrusions with 30 cells**



**U-loop 0.8 mm**
**wavelength**
**shifting fiber**
**in each cell**

# TASD: 25 kTons

- Similar PVC extrusions
  - thicker cells along the beam
    - 4.5 cm vs. 2.56 cm (more light)
  - Longer extrusions
    - 17.5 m long vs. 48 ft (less light)
  - 32 cells wide vs. 30 cells
    - Matches 16 channel APD
- Still Liquid Scintillator
  - **85% scintillator, 15% PVC**
  - **~Same price implies a detector with ½ the mass**
- Same U-Loop fiber
- Same APD readout
  - But only on two edges now




**APD readout on TWO edges**

Detector is wider & taller, but shorter along the beam

No crack down the center

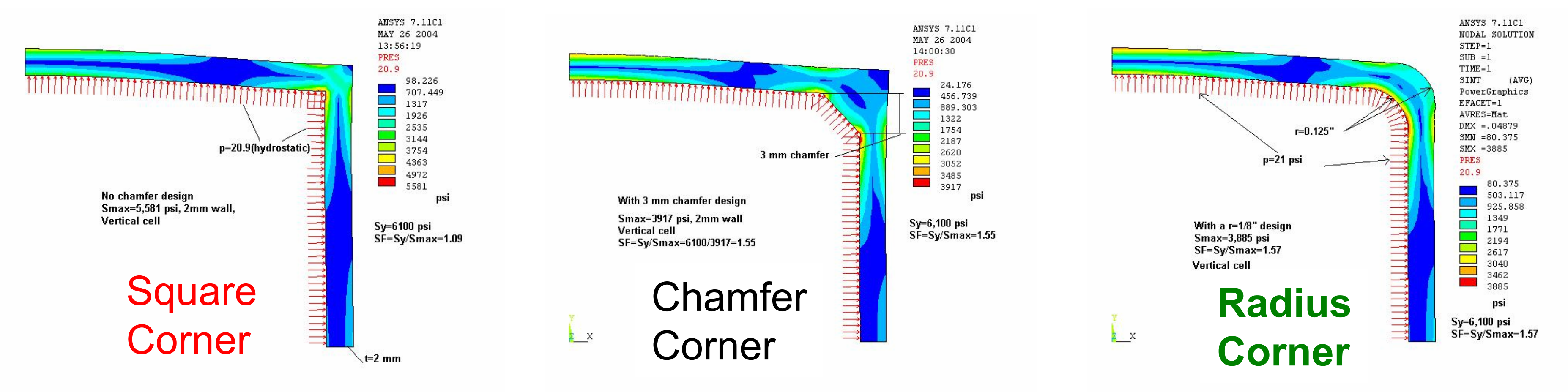
Least light areas are at the left And bottom edges

# This seems quite attractive

- Only 25 kT, but
  - the oscillated $\nu_e$ efficiency is higher (32% vs. 18%),
    - so the Figure of Merit (FoM = signal /sqrt(background) ) for 125 kT-yrs is ~ equal to the baseline with 250 kT-yrs with 4 x $10^{20}$ protons per yr
  - The detector has ~4 times as many hits per unit of track
    - (2.5cm liquid + 17.8 cm particleboard) → 4.1 * (4.5cm liquid + 0.4cm PVC)
    - With pulse height information in every sample
  - The detector has better energy resolution
    - Very high sampling fraction since 85% liquid scintillator
  - All at about the same cost

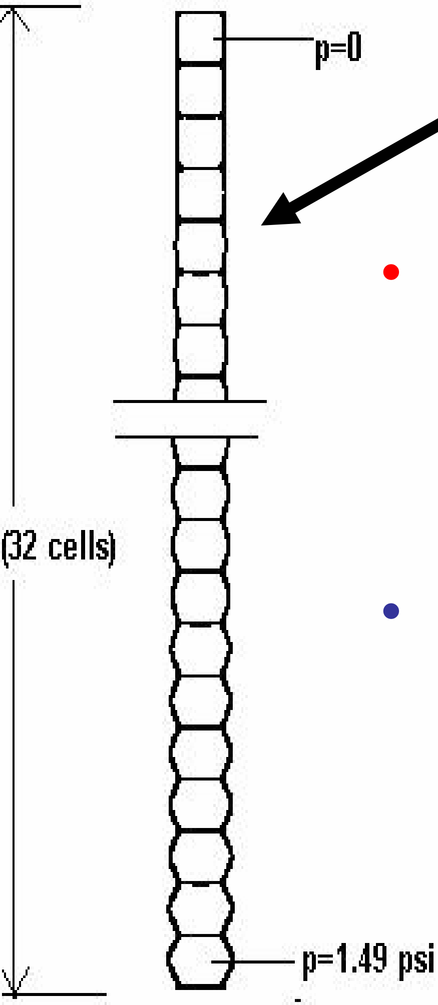
# Can we build TASD out of PVC?

- **A 5 story building constructed entirely with 2 mm thick PVC would be unique**
  - Properties of rigid PVC:
    - tensile yield of 6100 psi,
    - Tensile or elastic modulus of 0.360 Mpsi (particle board is 0.4 Mpsi)
- Some simple analysis steps -- First look at a single vertical cell
  - filled with 17.5 m of liquid, you get a pressure of 21 psi
  - Typical design maximum stress is 67% of yield, i.e. a safety factor of 1.5



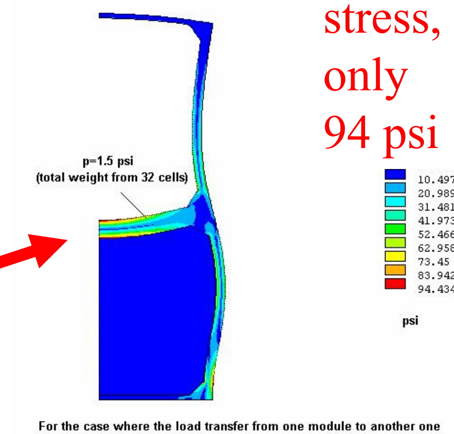

- **Encouraging finite element results** *(clearly need to test this)* :
  - Square corner SF=1.09, Chamfer corner=1.55, **Rounded corner =1.57**

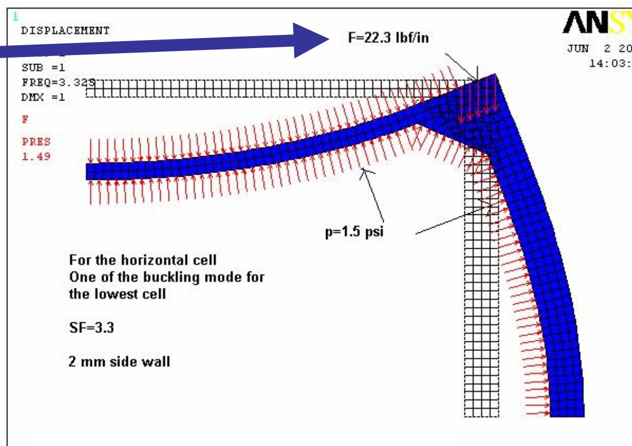
# How about the horizontal cells?




- Within one 32 cell high extrusion,
  - the liquid pressure just builds up to 1.5 psi = (1/14) of the vertical cell case since 14 extrusions are stacked on one another
- Between extrusions we get an effective 4 mm thick wall
  - the load gets transferred by this 4 mm to the side walls like the rungs do on a ladder
- Finally the load of the entire 17.5 m high stack ends up on the vertical wall in the lowest cell
  - We calculate a safety factor of 3.3 against buckling stress when 3.0 would be a normal design standard

modest stress, only 94 psi

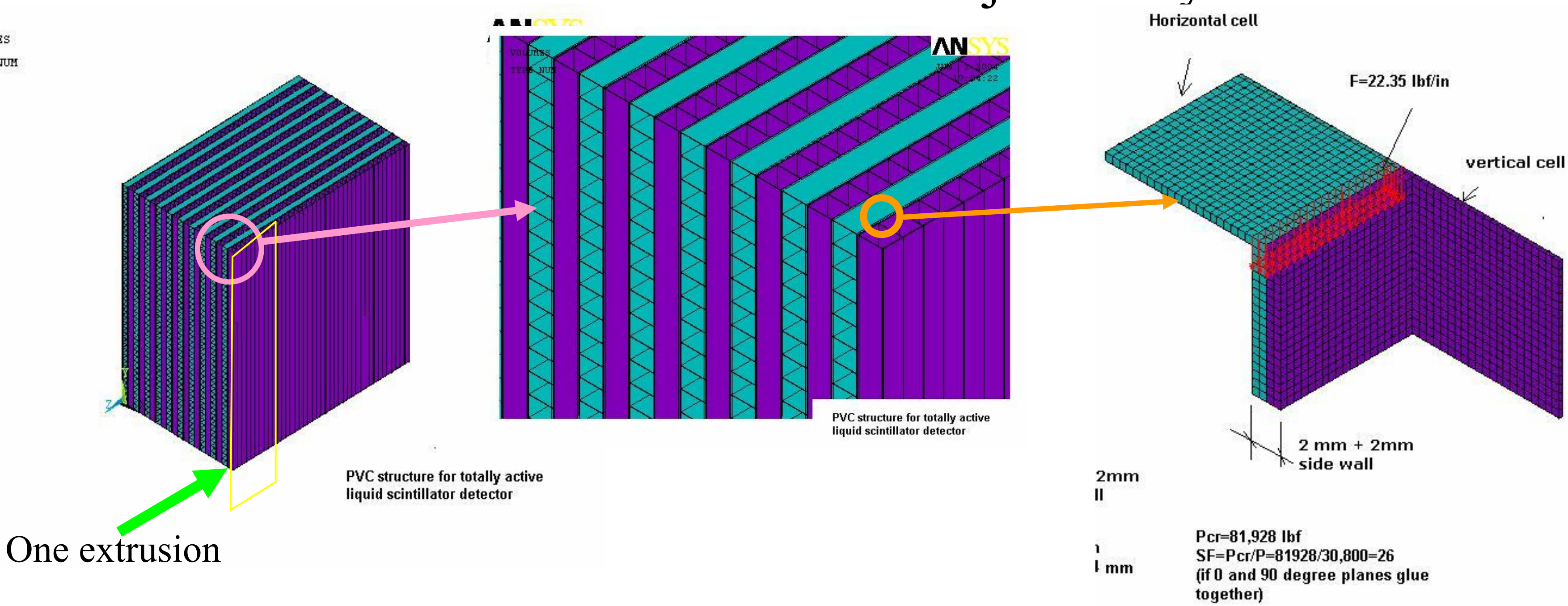



Safety factor of 3.3

# Stronger yet due to “honeycomb”

- So far, we haven’t included the buttress effect in one layer of cells from the cell dividers in the adjacent layer

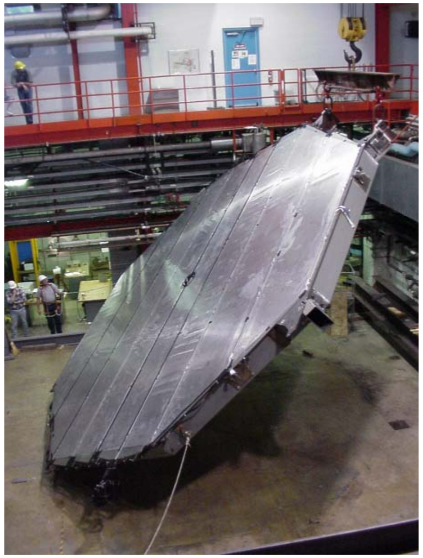



  - Finite element indicates a safety factor of > 20 if the two 2mm walls are perfectly bonded together (working stress of the 4mm has a SF of 4)
  - Similar results from independent “shell element” calculations

- **So we have some confidence this can be done**
  - More calculations and many actual tests are required.

# Installation

- Build larger 0.5m by $(17.5\ \mathrm{m})^2$ arrays on the floor and lift with a strongback a la MINOS
  - Tack weld extrusions together at crossed intersection points



- OR, take one extrusion at a time to the working face of the assembly and weld (or glue) it in place

- Fill with liquid later !
  - Rate of 15 gallons per minute

- Assemble the entire object and fill it in about two years
  - Assemble the extrusion modules over four years in several factories
  - allows for a building construction period before we need the building

PVC welding with a dual-tipped tool at $300^0$C.

Like a hot Glue gun

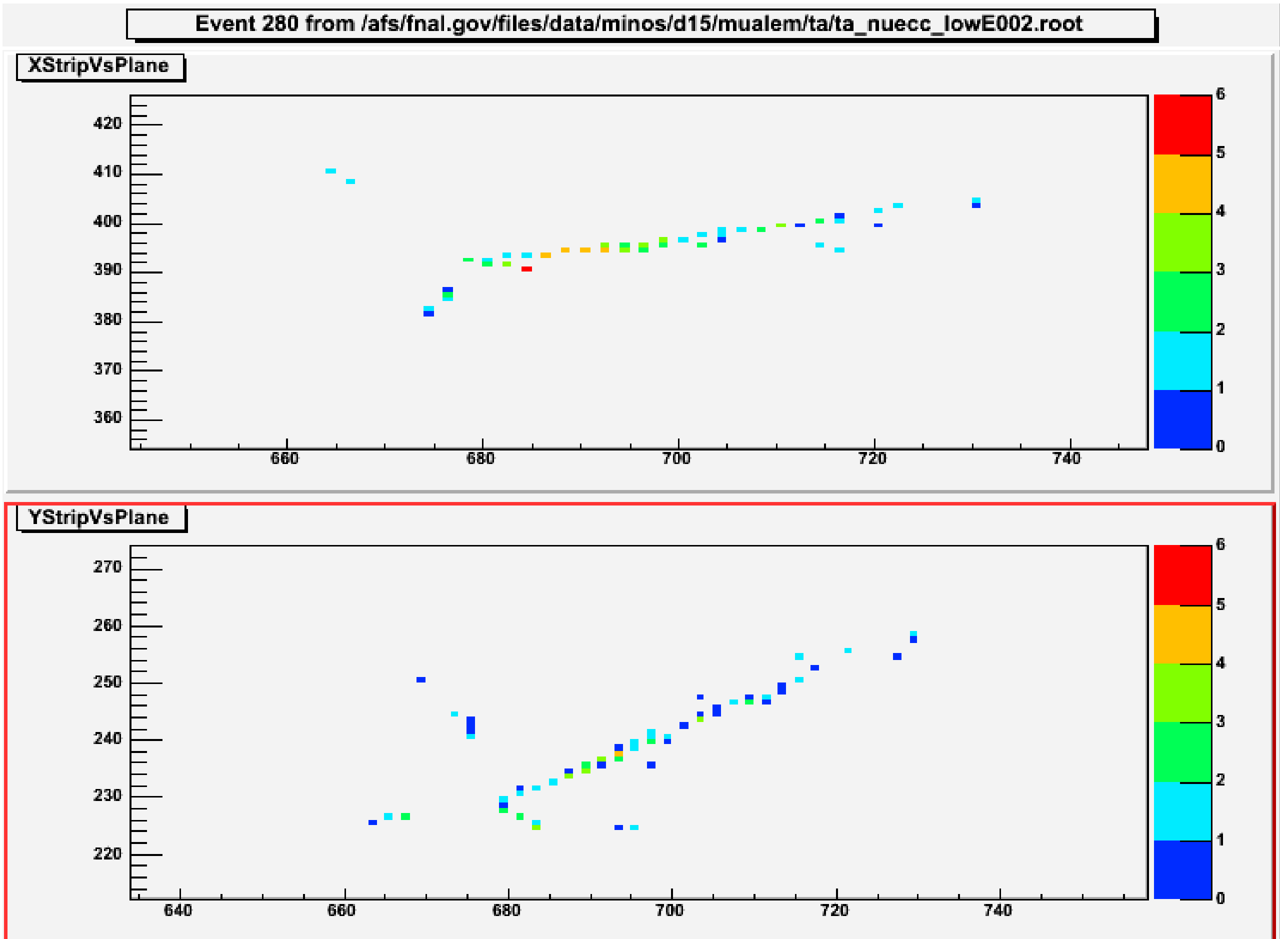
# Scintillator Photon Economics

- **Start with known MINOS parameters**
- .95 pe/mip @ 15 m with 1.2 mm fiber with photomultiplier and MINOS solid scintillator (1 cm thick)

- **Liquid Scintillator Baseline Changes**
- 10.6 pe @ 15 m with APD
  - (*1.4 from spectrum and *8 from QE at peak)
- 42.5 pe @ 15 m with fiber in a U loop
  - (*4 from 2 fibers each with perfect mirrors)
- 28 pe @ 15 m with 0.8 mm fiber
  - (*0.67, just ratio of diameters)
- 42 pe @ 15 m with liquid scintillator
  - ( *1.5 since 2.56 cm thick x 4 cm wide cell gives more photons produced and more advantageous light collection geometry)
- **Verifying this reasoning chain is a critical R&D test**

- **Totally Active adds:**
- 42 pe @ 17.5 m, but with 4.5 cm thick cell
  - ( *1.75 more light but *0.5 for poorer light collection in thicker cell and *.86 for attenuation in longer fiber)
- **Increase cell thickness along the beam direction but balance by a longer cell transverse to the beam**

# TASD Performance: Event pictures




The color code indicates the relative pulse height

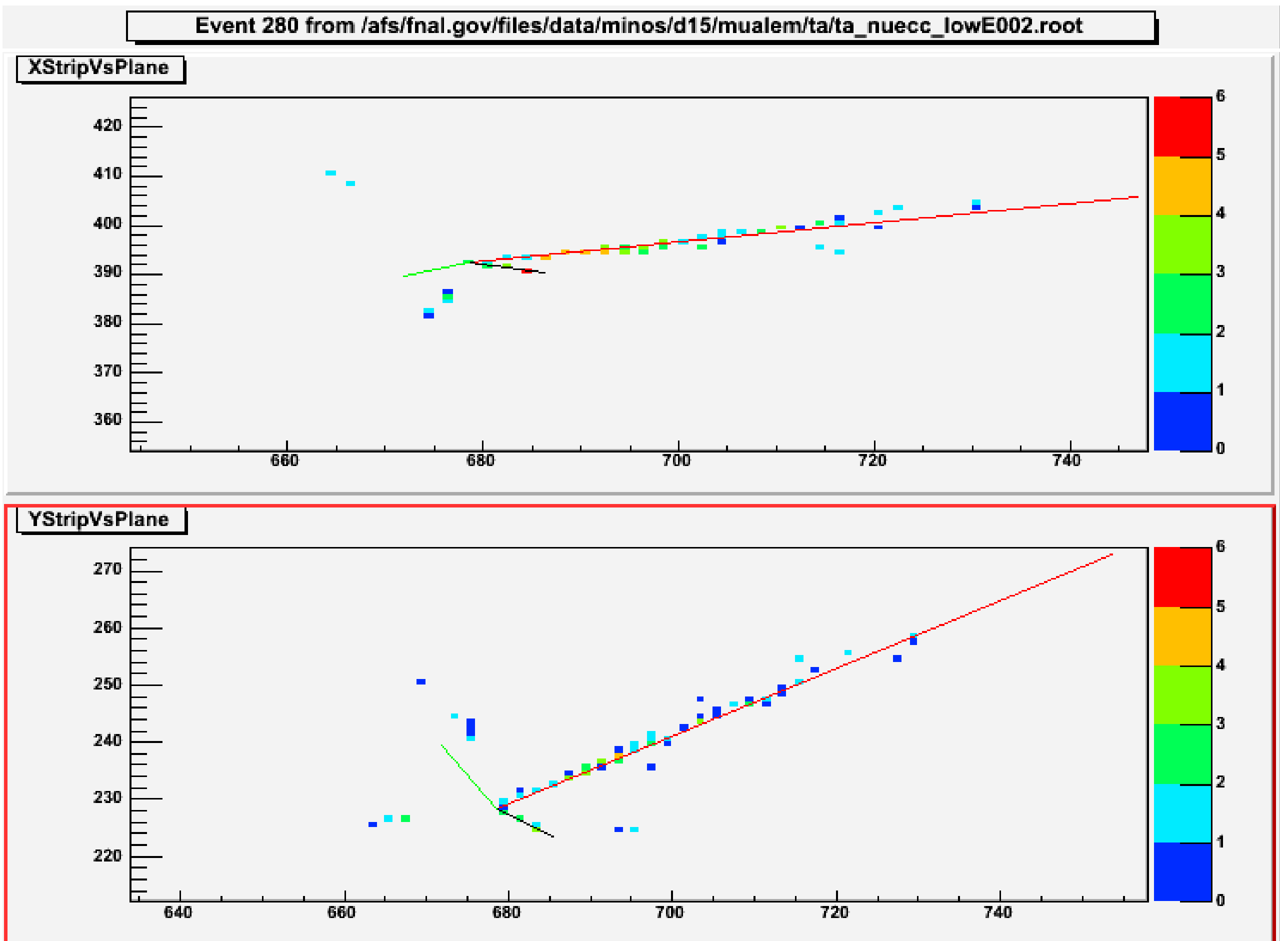
The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

**<u>Usual kinds of pattern recognition:</u>**

- Find tracks – each projection independent
- Look for vertex
  - sometimes it's difficult, tracks can go backwards
- Look for track ID
  - particularly "fuzzy" e's
  - long track, not fuzzy ($\mu$)
  - gaps in tracks ( $\pi^0$ ?)
  - large energy deposition (proton?)

# TASD Performance: event pictures

More of these at the end of the talk




The color code indicates the relative pulse height

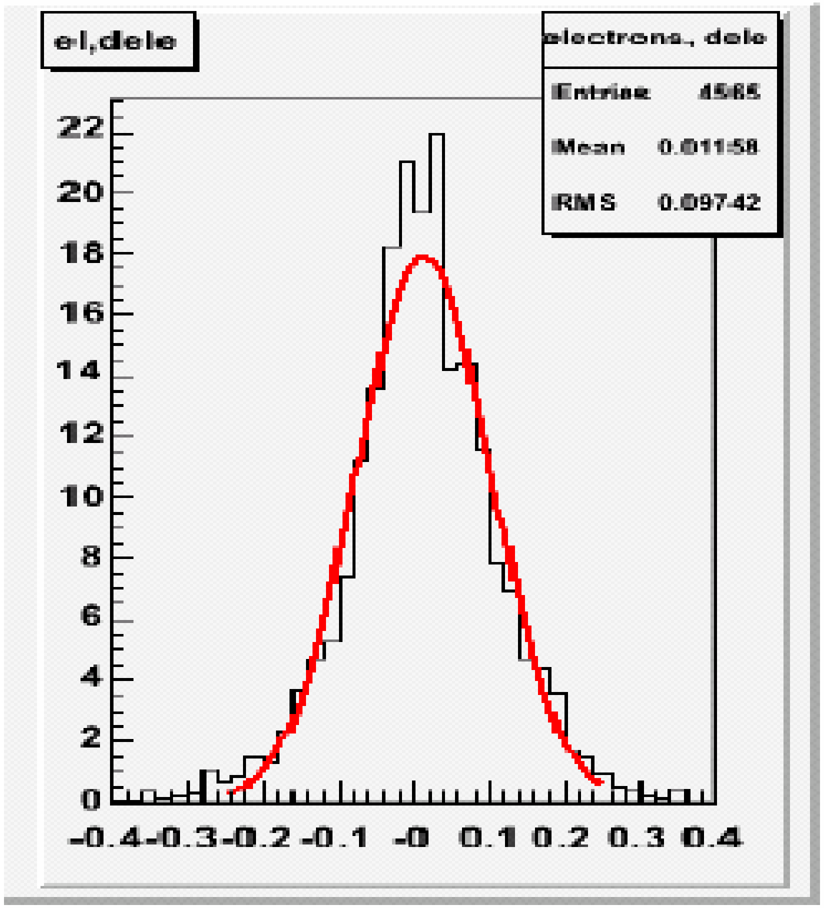
The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

The lines are the trajectories of the final state particles: charged leptons in red, charged pions in blue, protons in black, and neutral pions in green

The line length is proportional to energy, but NOT to the expected path length of the track

Good $\nu_e$ CC event, $\nu_e + A \rightarrow p + e^- + \pi^0$, $E_\nu = 1.65$ GeV

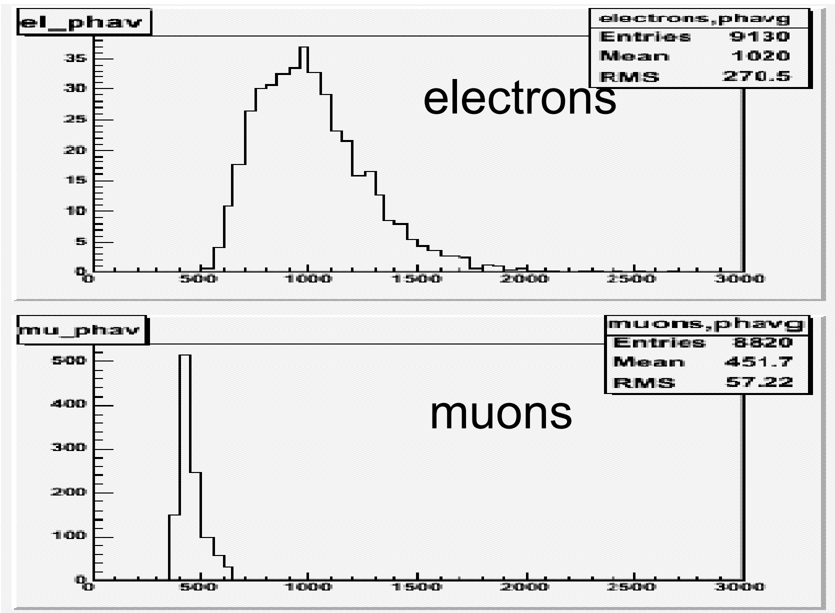
# TASD: Energy Resolution



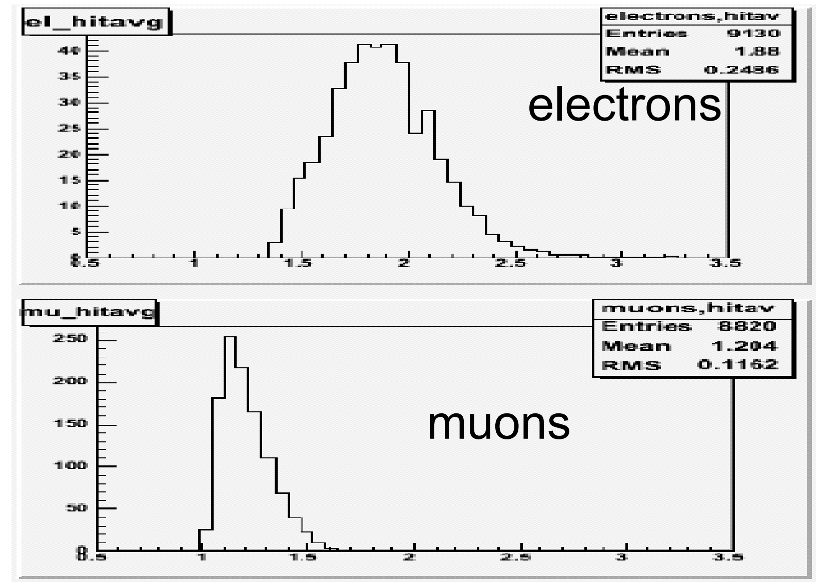

**Measured – true energy**
**divided by square root of true energy**

- For $\nu_e$ CC events with a found electron track (about 85%), **the energy resolution is about 10% / sqrt(E)**
- This helps reduce the NC and $\nu_\mu$ CC backgrounds since they do not have the same narrow energy distribution of the oscillated $\nu_e$'s

# TASD $\mu$ / e separation




Average **pulse height** per plane



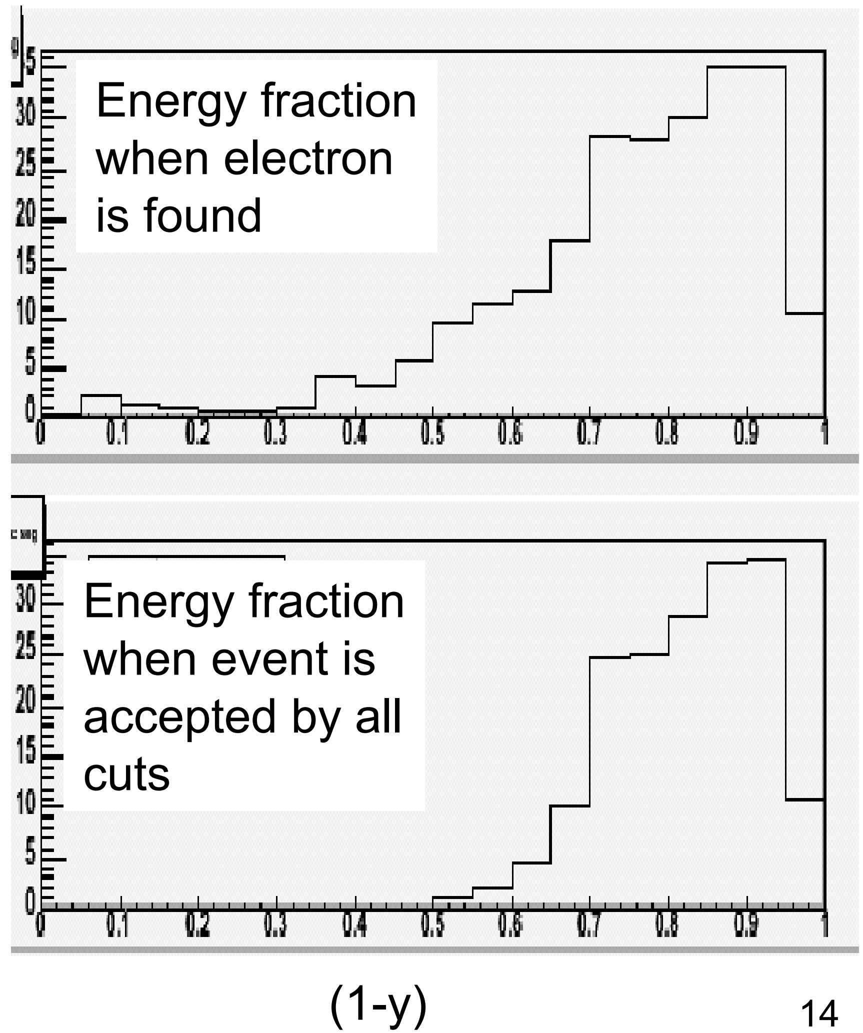

Average **number of hits** per plane

- This is what it means to have a "fuzzy" track
  - Extra hits, extra pulse height
- Clearly $\nu_\mu$ CC are separable from $\nu_e$ CC

# TASD $\nu_e$ Signal efficiency

- Find a good electron
  70% of the time
  - 32% (about half of the 70%) get accepted by full analysis
  - These are predominately at high (1-y), high fraction of energy in the electron
- Find a wrong electron
  15% of the time
- No electron found
  15% of the time

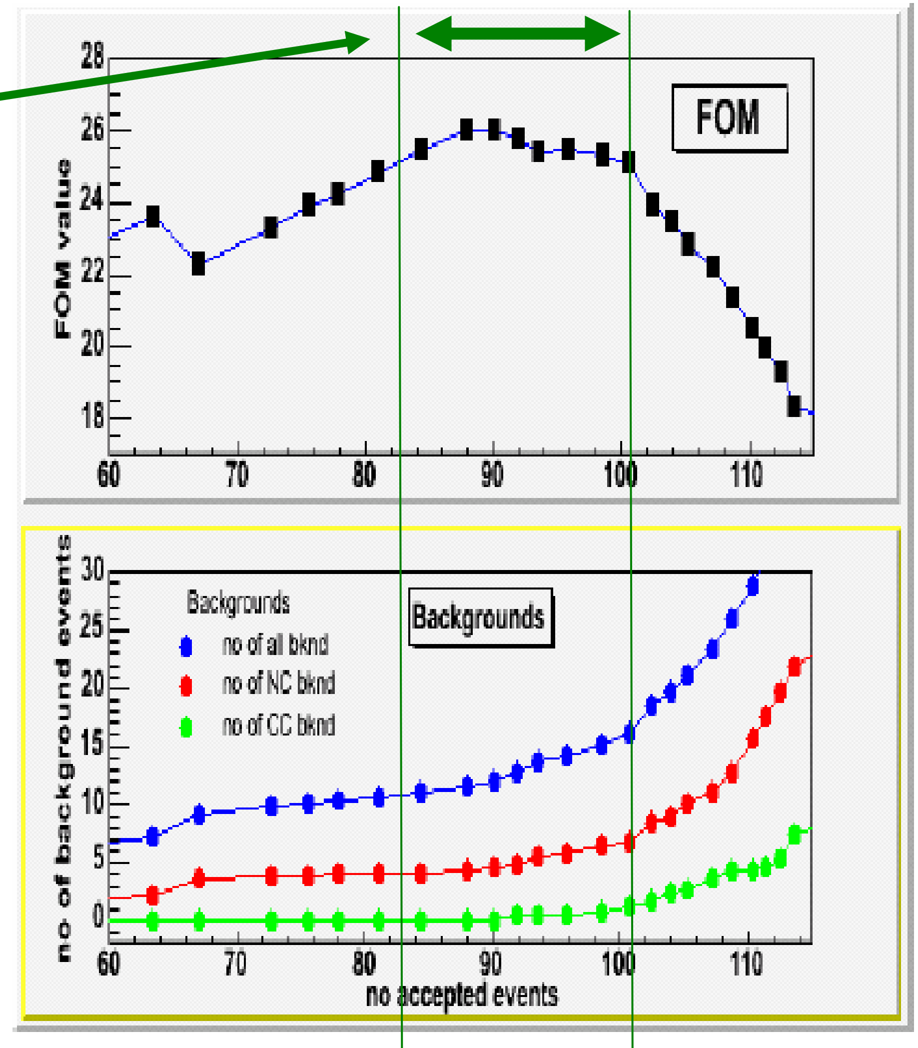
- Still believe we can work on
  - the 28% with low (1-y) and
  - the 30% with no/wrong electron
  - to get higher efficiency



# TASD net performance

## With typical cuts, find

- **90 – 110 $\nu_e$ signal events**
- **5 – 7 beam $\nu_e$ events surviving**
  - (hard to reduce, same energy dist.)
- **2 – 3 $\nu_\mu$ CC background events surviving**
  - (already small)
- **4 – 6 NC background events surviving**
  - ($\pi^0$ faking an electron, maybe can reduce)
- **Figure of Merit ~ 27**
  - Reducing NC by half would increase this to 34
  - All for 125 kT-yrs @ 4 x $10^{20}$ prot/yr




**Scale # events in plot by 1.08 for 4 x $10^{20}$**

# TASD Cost Estimate

- Done at the same level of detail as the Baseline

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | 50 kT<br>Liquid Scintillator Baseline | | 25 kT<br>Totally Active Scintillator Detector | | | |
| | | | | | | Delta from Liq Scint Sub-total | |
| WBS | Description | Base Cost | Incl Overhead & Contingency | Base Cost | Incl Overhead & Contingency | Sub-total | |
| 1.0 | Near Detector | 2,152,582 | 5,166,198 | 3,576,039 | 8,582,494 | 3,416,296 | only 30% "totally" active |
| | | | | | | | M64, MINOS Near Elec., |
| 2.0 | Far Detector | | | | | | more channels drives cost |
| 2.1 | Absorber | 12,618,525 | 16,804,304 | 0 | 0 | (16,804,304) | none in this design |
| 2.2 | Active Detector | 28,324,540 | 39,023,945 | 63,085,322 | 84,321,021 | 45,297,076 | more extrusions, fiber, and liquid |
| 2.3 | FEE, Trigger and DAQ | 6,375,205 | 10,945,290 | 8,335,880 | 14,220,877 | 3,275,587 | more channels |
| 2.4 | Shipping&Customs Charges | 5,421,343 | 7,860,947 | 4,290,330 | 6,220,979 | (1,639,969) | no absorber, but more oil |
| 2.5 | Installation | 11,789,067 | 20,520,401 | 6,050,554 | 10,513,009 | (10,007,391) | similar crew, but half the time |
| | ***Detector Sub-total*** | 64,528,679 | 95,154,888 | 81,762,086 | 115,275,886 | 20,120,998 | to install |
| | | | | | | | |
| 3.0 | Building and Outfitting | | | | | | |
| 3.1 | Building | 16,634,800 | 27,105,127 | 12,093,380 | 19,705,232 | (7,399,895) | shorter, but $5M fixed site costs |
| 3.2 | Outfitting | 4,745,748 | 9,776,240 | 4,589,748 | 9,454,880 | (321,360) | no active shield support |
| | ***Building and Outfitting Sub-total*** | 21,380,548 | 36,881,367 | 16,683,128 | 29,160,112 | | |
| | | | | | | | |
| 4.0 | Active Shield | 1,602,882 | 4,039,262 | 0 | 0 | (4,039,262) | assume self-shielding |
| | | | | | | | |
| 5.0 | Project Management | 3,935,000 | 6,024,780 | 3,935,000 | 6,024,780 | - | assume identical |
| | | | | | | | |
| **TPC** | **Total Project Cost** | **93,599,690** | **147,266,495** | **105,956,253** | **159,043,273** | 11,776,778 | |

# Compare Designs

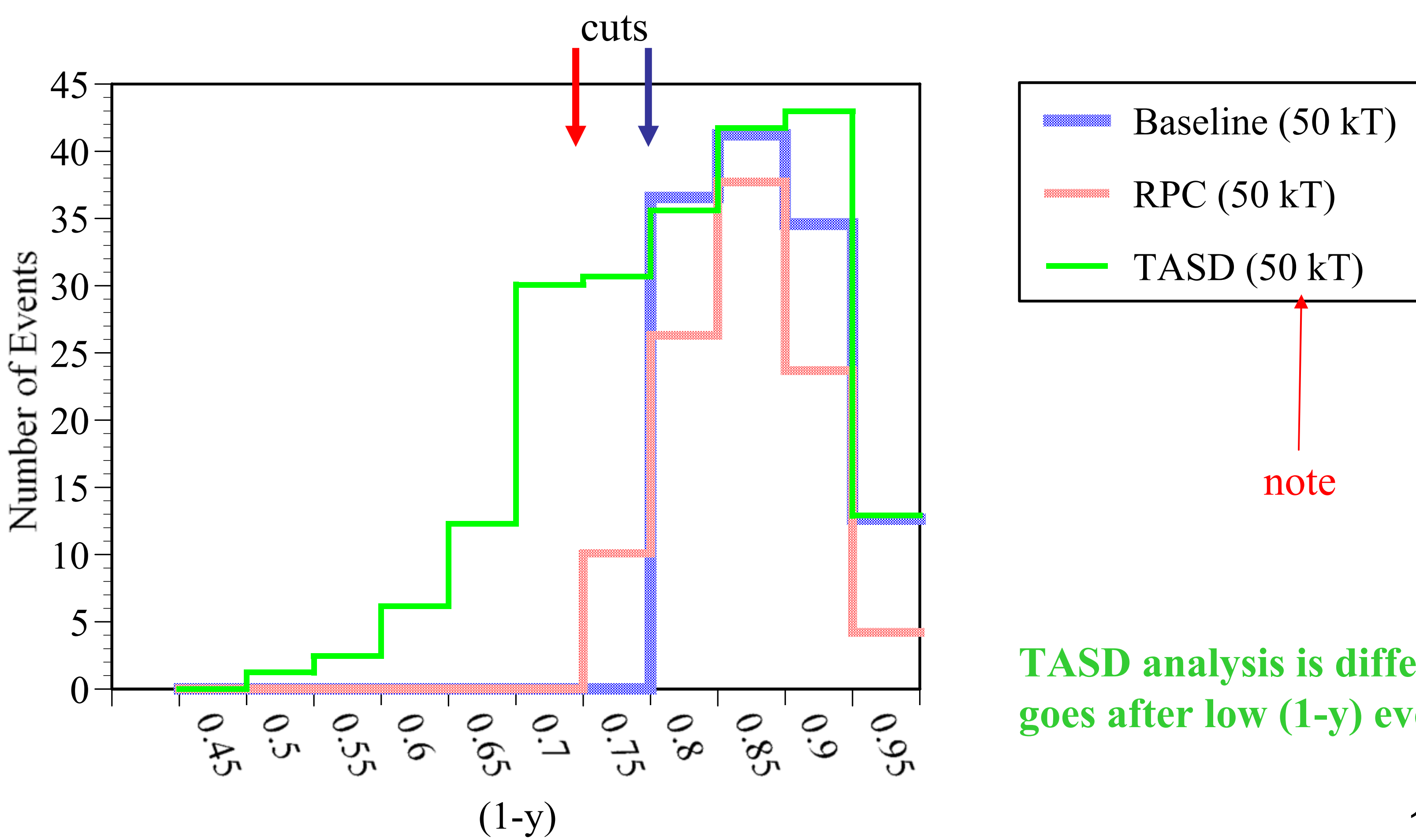
- **We finally have managed to compare**
  - the Baseline (without pulse height) to
  - the RPCs with only X or Y measurement at each layer
- **That is, apple to apples** (except different analyses to find the apples)
  - This exposed some bugs
    - largest: containment volume in Baseline – of course this reduced the signal, sigh
  - gives us confidence in both analysis methods

| | RPC (1 readout per layer) | Baseline (no Pulse Height) | Baseline (with Pulse Height) | RPC ( X & Y readout / layer) |
|---|---|---|---|---|
| Baseline Analysis | 108 signal / *26 background* (FoM = 21.0) | 135 signal / *31 background* (FoM = 24.3) | 141 signal / *28 background* (FoM = 26.8) | |
| RPC Analysis | 112 signal / *34 background* (FoM = 19.3) | 123 signal / *34 background* (FoM = 21.0) | | 123 signal / *25 background* (FoM = 24.4) |
| each individually optimized | | | | |
| 810 km, 10 km off-axis, 250 kT yrs with 3.7 x $10^{20}$ prot/yr | | | | |

Expect all these to be "the same"

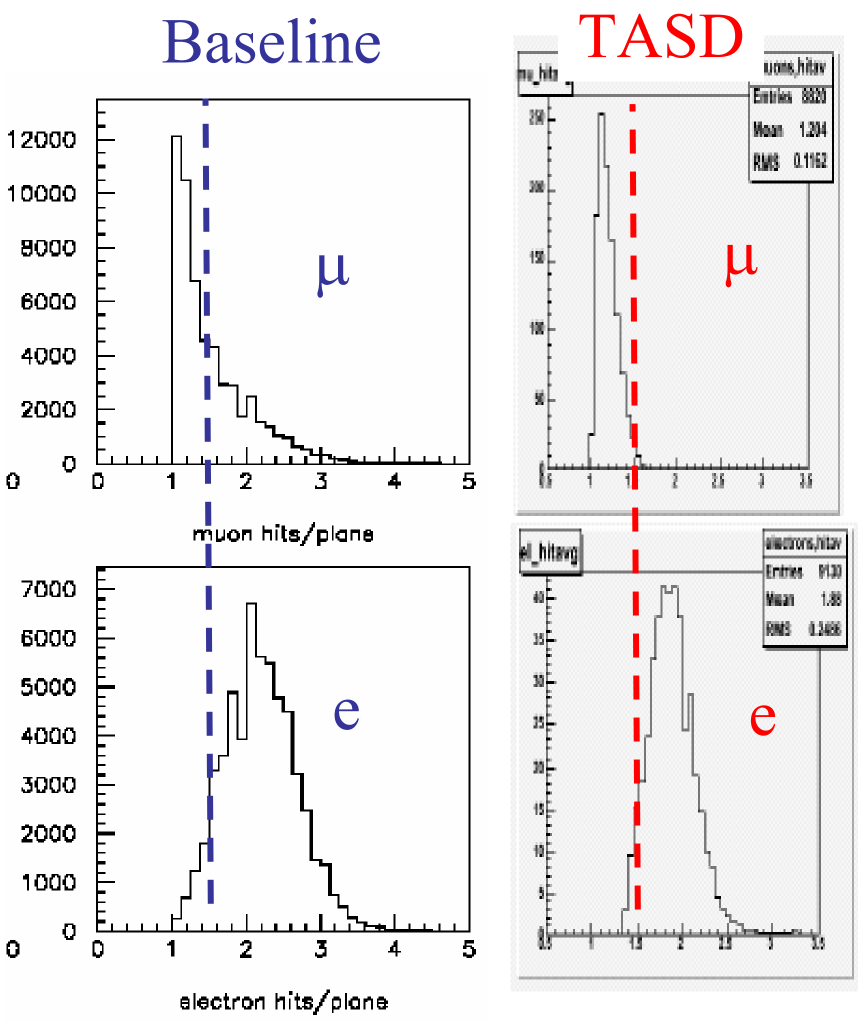
# Compare Designs

- **Efficiency vs. (1-y)**




**TASD analysis is different: goes after low (1-y) events**

# Compare Designs

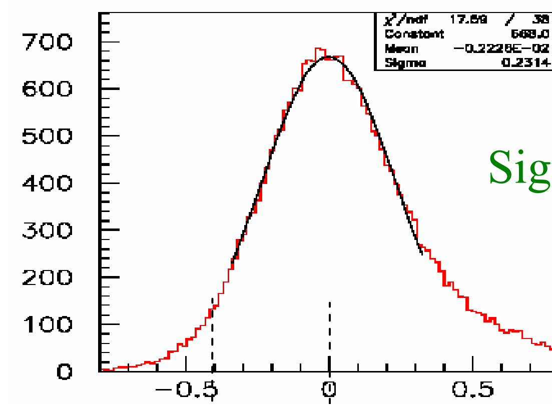



Hits per plane

- **e / μ separation**
  - Measure of "fuzzy"
- TASD distributions are narrower than Baseline
  - If cut at 1.5 hits/plane
  - TASD nearly separated
  - Baseline has ~40% μ above cut
- Similar for Pulse Height per plane

# Compare Designs

- **Energy resolution**
  - sampling digital hits only
    - > sampling pulse height
      - > totally active



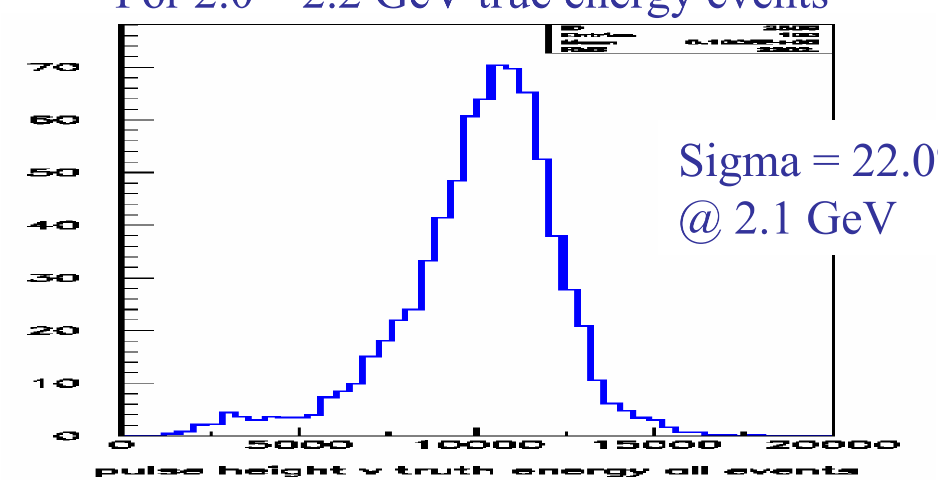

RPCs

Sigma = 23.1%

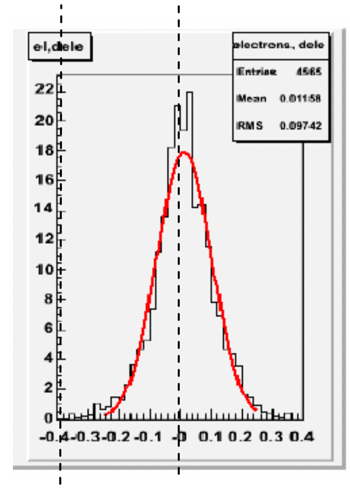
These two are (Meas-True)/sqrt(True)

**Baseline** event pulse height

For 2.0 – 2.2 GeV true energy events




Sigma = 22.0%
@ 2.1 GeV



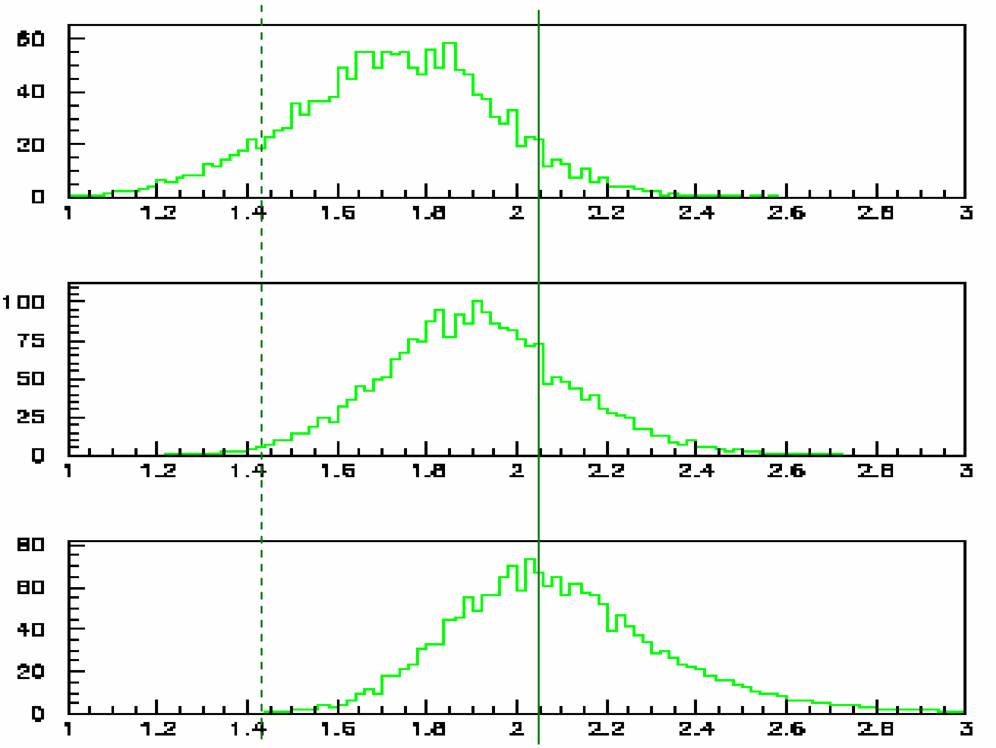

TASD

Sigma = 9.7%

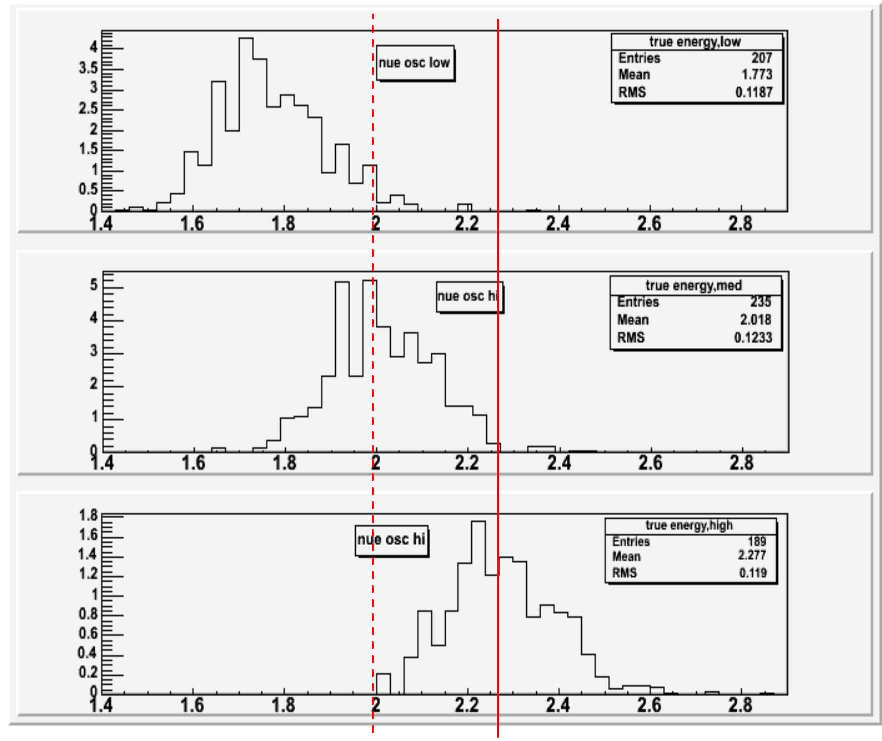
So for (Meas-True)/sqrt(True), sigma = 15%

# Possible use of energy resolution

For accepted events, divide the sample into three equal parts by measured energy, then plot true energy, could separate (w high statistics) into E bands = change off-axis distance




True $\nu_e$ CC energy (GeV)
For accepted events,
RPC design




True $\nu_e$ CC energy (GeV)
For accepted events,
TASD design

# Compare Detector Designs

| Parameter | RPCs | Baseline Liquid Scintillator | TASD | | |
|---|---|---|---|---|---|
| | | | | | @ 810 km, 12 km off-axis, |
| **Exposure** | **250 kT-years** | **250 kT-years** | **125 kT-years** | | and 4 x $10^{20}$ prot / year |
| **Signal** | **102** | **125** | **108** | | |
| **Background** | **14.6** | **26** | **16** | | |
| NC background | 4.0 | 11.3 | 7 | | 1 event = 1.9 x $10^{-4}$ rejection |
| $\nu_\mu$ CC background | 0.3 | 1.2 | 2 | | 1 event = 6.3 x $10^{-5}$ rejection |
| $\nu_e$ beam background | 10.3 | 13.7 | 9 | | 1 event = 2.5 x $10^{-3}$ rejection |
| | | | | | |
| **Figure of Merit** | **26.7** | **24.5** | **~27** | | |
| | | | | | |
| **Oscillated $\nu_e$ Eff.** | **15%** | **18%** | **32%** | | |
| **Energy Resolution * $(E)^{1/2}$** | **23%** | **15%** | **10%** | | |
| | | | | | |
| **Cost** (incl. overhd + contingency) | **≥ $ 150 M** | **$ 147 M** | **$ 159 M** | | |

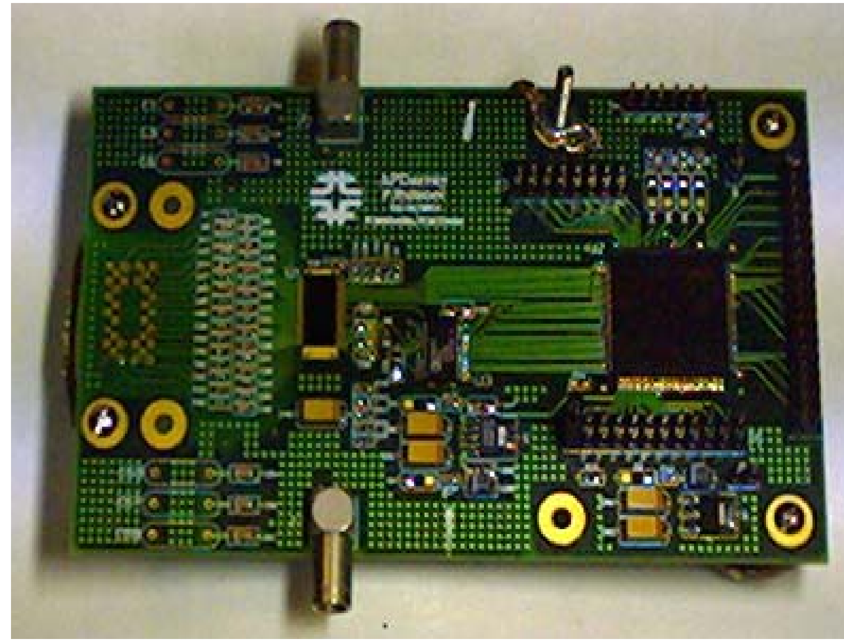
# R&D Status, Plans

- **Our R&D efforts are now totally focused on liquid scintillator designs**
  - Not an official technology decision yet (pending liquid design R&D), but the collaboration is converging
  - RPC and solid scintillator are backups on the R&D back burner

- **3 Main efforts**
  - Understand the light output from long liquid scintillator cells, including the waveshifting fiber and APD readout
    - More details in a moment
  - Cosmic Ray Background test, overburden question
    - Trying now to get some MINOS solid scintillator modules and MINOS electronics for this test
  - More detector simulations and analysis
    - Optimize cell width & thickness
    - Work for higher efficiency and more background rejection
    - More analyses & tests of the PVC structure

# Light output R&D

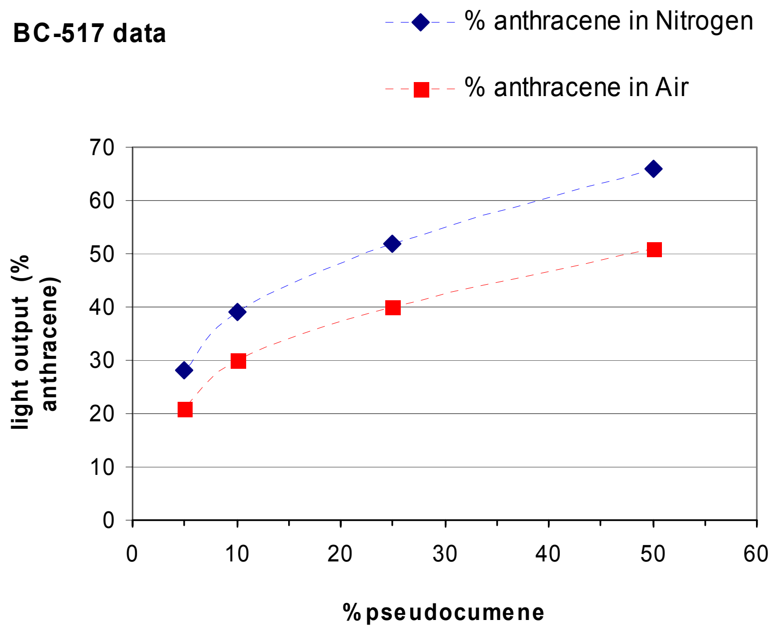
- 2nd generation APD
  + Fermilab MASDA
  low noise amp chip
  - **Have now demonstrated 350 electrons noise**
    - Operating at a gain of 100 and at a temperature of $-15^{0}$C

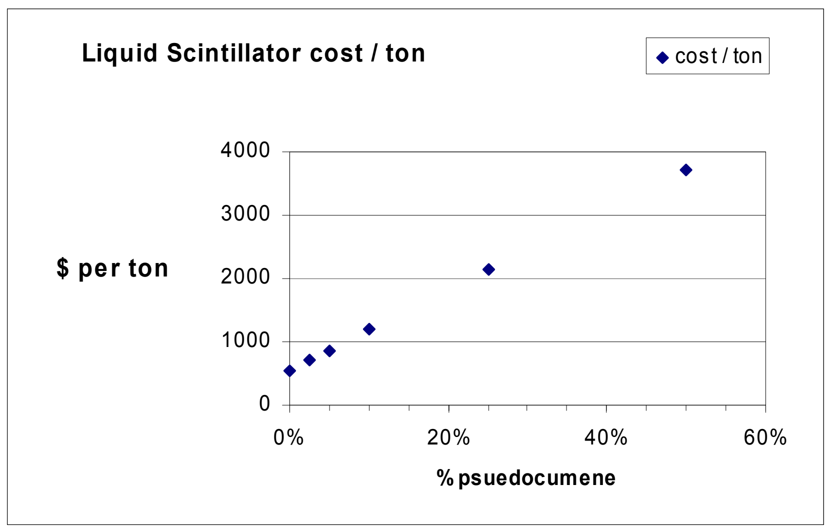


  - **Good news: This was our spec in the proposal**
    - Driven by desire for S/N of 10/1
    - 42 pe on slide #9, * 85% QE of APD, * gain of 100 = 3570 electron signal
    - Clearly, lower noise yet would imply we could live with less light
  - **R&D on multiple correlated sampling vs. 1 before + 1 after holds promise of 200 electrons noise (J. Oliver)**

# Light output R&D

- **Fluor (psuedocumene + PPO + POPOP) fraction**
  - Our TASD cost estimate uses 10% Fluor, 90% mineral oil
  - If reduce this to 5% Fluor, get 67% of the light
  - And, save \$ 318 / ton on 21,150 tons = \$ 6.7 M
- **R&D on fluor mixtures to see what we can save**
  - OR, what additional TASD mass could we afford ?

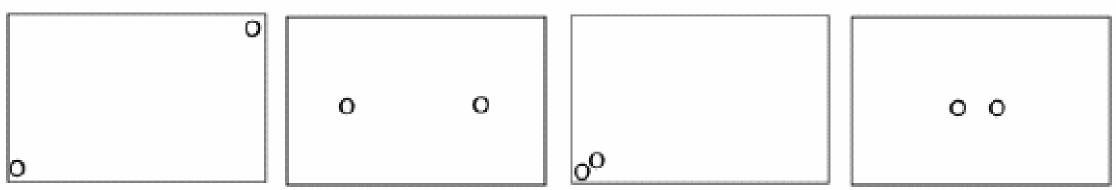


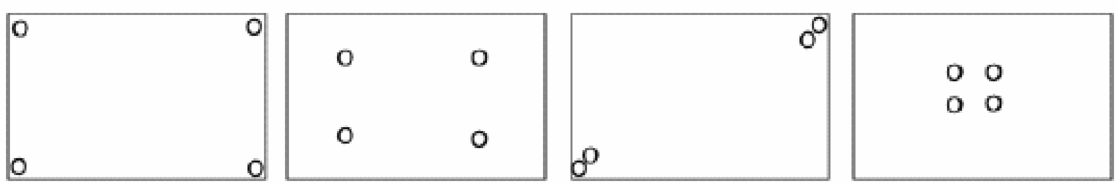
# Light output R&D

- **Different Fiber schemes simulated**
  - FOUR 0.5 mm fibers give light ~ equal to TWO 0.8 mm fibers
  - Fiber cost proportional to volume
    - $(0.5)^2 = 0.25$ $(0.8)^2 = 0.64$
    - So volume is 40% of that in our TASD cost estimate
- For 32,000 kilometers of fiber would save $ 5 M
    - OR, what additional TASD mass we could afford ?
    - **R&D needed to verify simulations**

Positions studied
in simulations
For 2 fibers

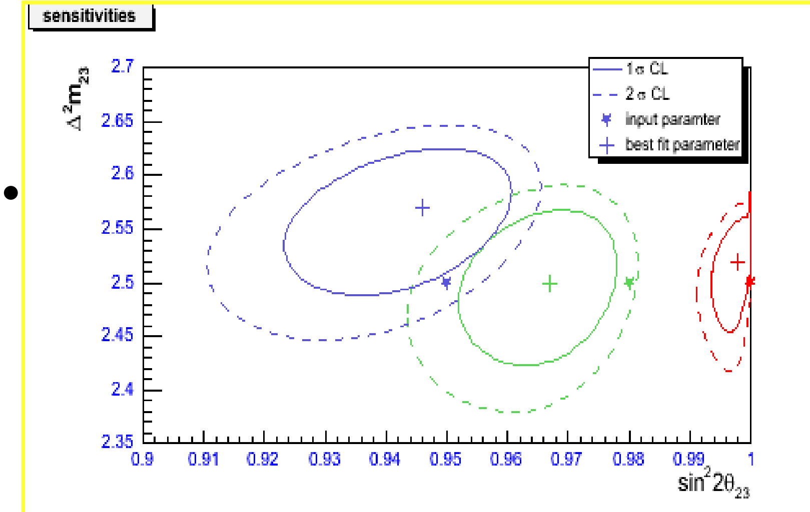


Positions studied
in simulations
for 4 fibers



# Summary

- **Totally Active Scintillator looks better and better.**
  - Can even do other physics, e.g. with $\nu_\mu$ quasielastics
  - Handle on $\Delta m^2_{32}$ vs $\sin^2 2\theta_{23}$




- **We are focused on R&D for liquid scintillator.**
- **We are still asking for Stage 1 Approval.**
  - The overall approval process is very long (witness BTeV)
    - We want to start that process
    - No shortage of off-ramps between here and funds
  - Meanwhile, the off-axis beam on-ramp appears early next year

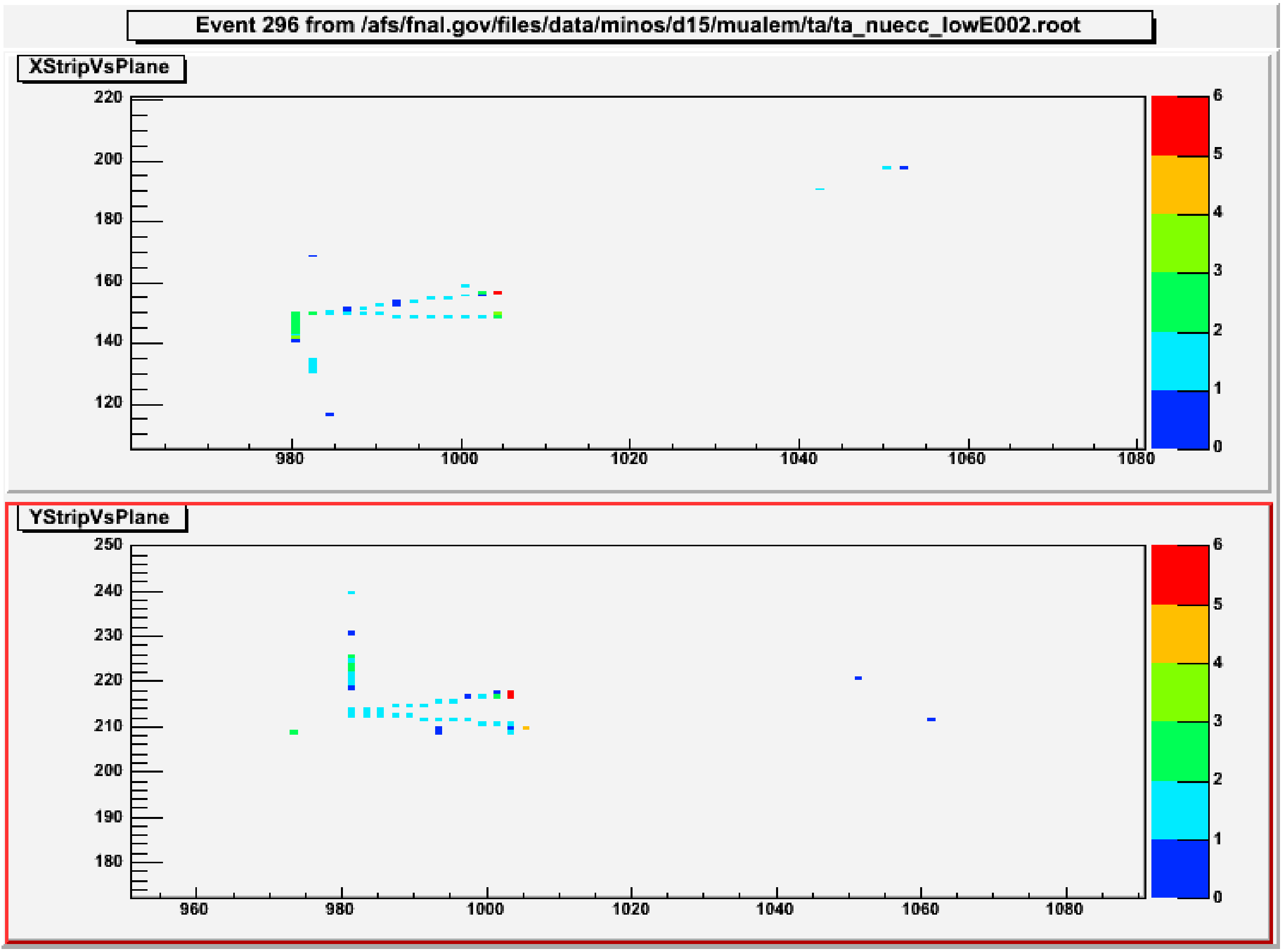


- (additional event pictures follow)

# Additional Event Pictures

- The following slides come in pairs:
  - First picture is just the raw information
    - So you can try your own identification
  - Second picture has the event identification and tracks

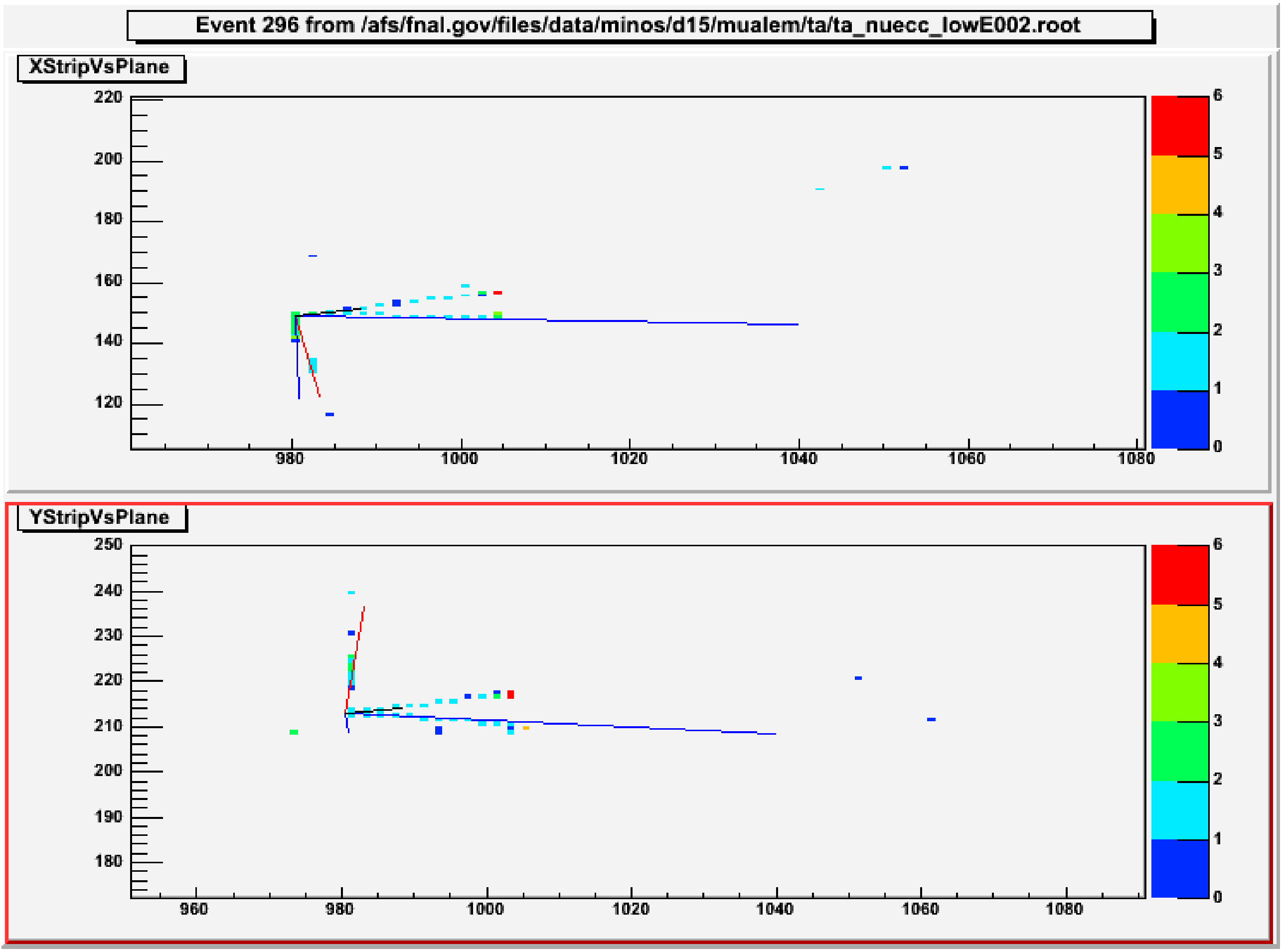
# Event #2




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

# Event #2




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

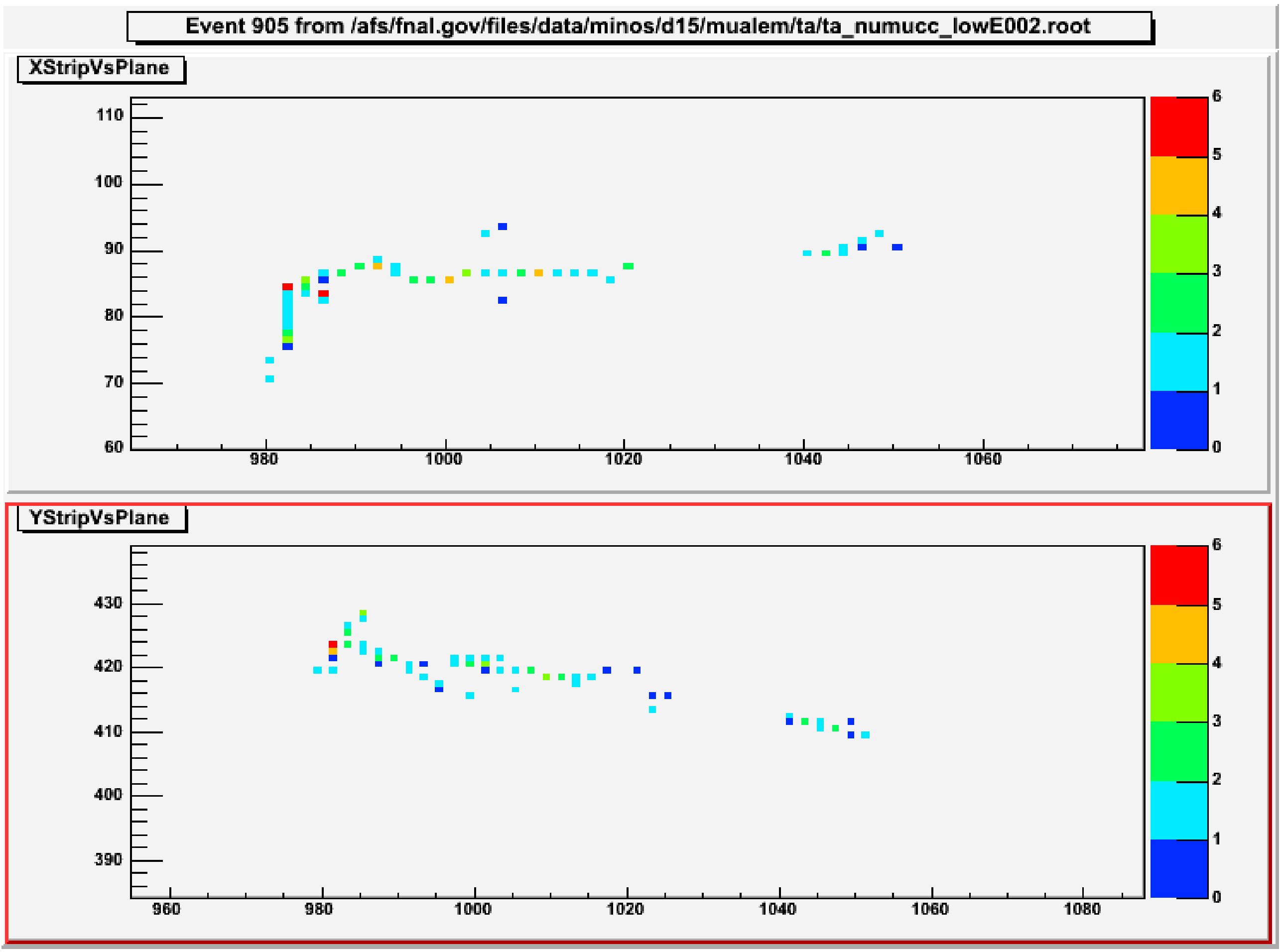
The lines are the trajectories of the final state particles: charged leptons in red, charged pions in blue, protons in black, and neutral pions in green

The line length is proportional to energy, but NOT to the expected path length of the track



A $\nu_e$ CC event which fails, $\nu_e + A \to p + e^- + \pi^+ + \pi^-$, $E_\nu = 1.87$ GeV

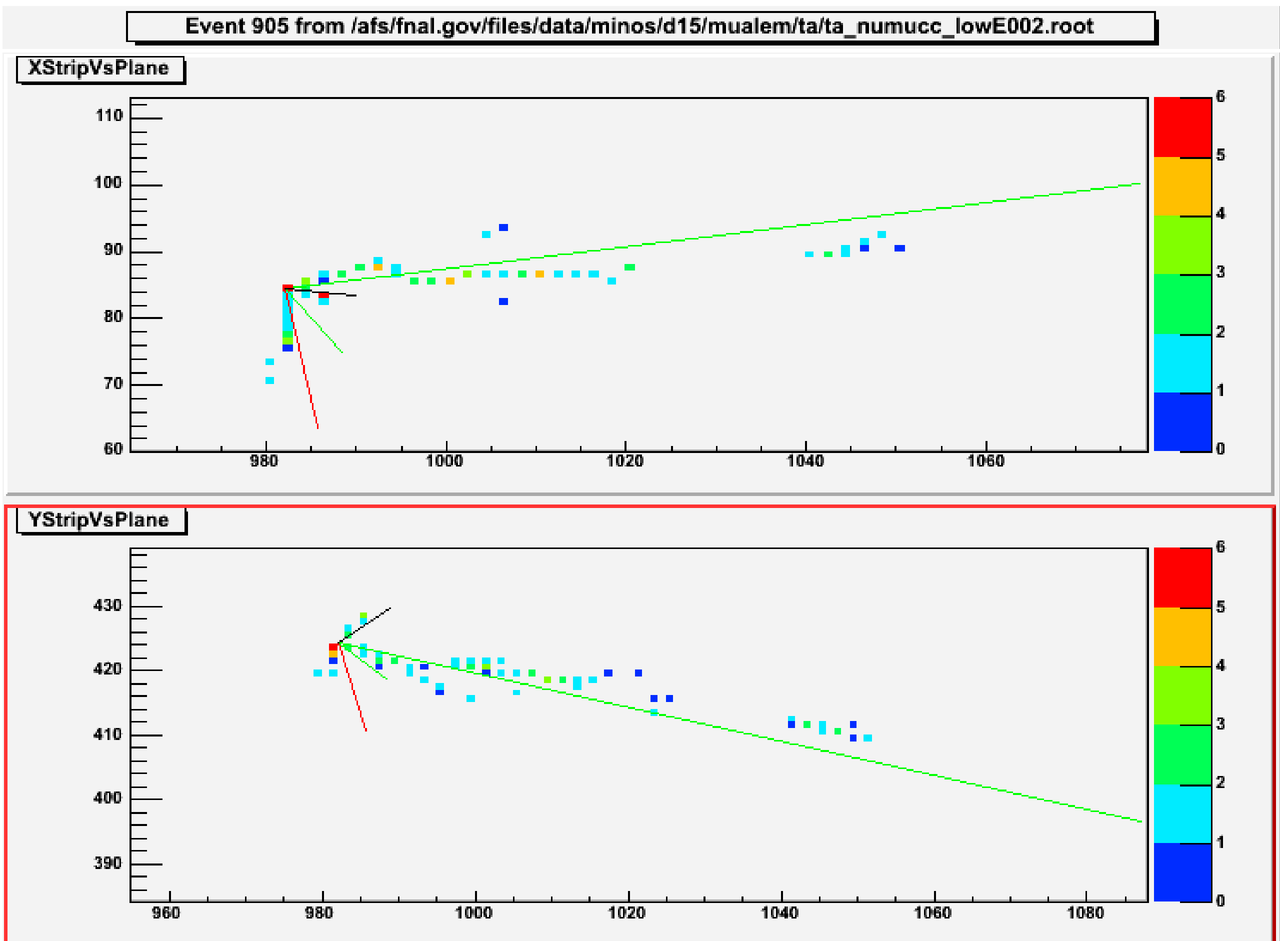
# Event #3




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is
4.9 cm horizontal axis
4.0 cm vertical axis

# Event #3




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

The lines are the trajectories of the final state particles: charged leptons in red, charged pions in blue, protons in black, and neutral pions in green

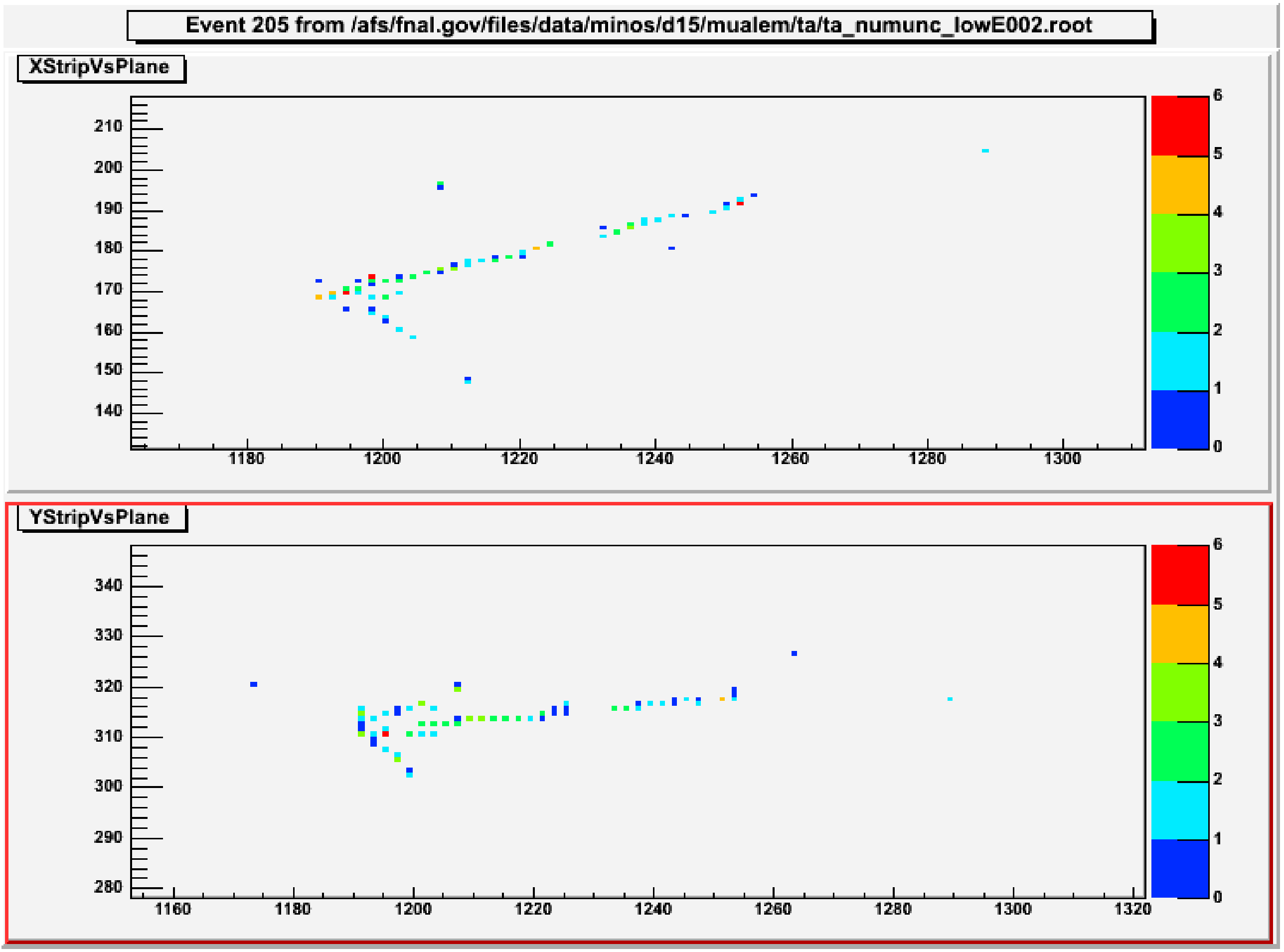
The line length is proportional to energy, but NOT to the expected path length of the track



A background $\nu_\mu$ CC event, $\nu_\mu$ + A -> p + $\mu$- + $\pi^0$+ $\pi^0$ , $E_\nu$ = 1.70 GeV

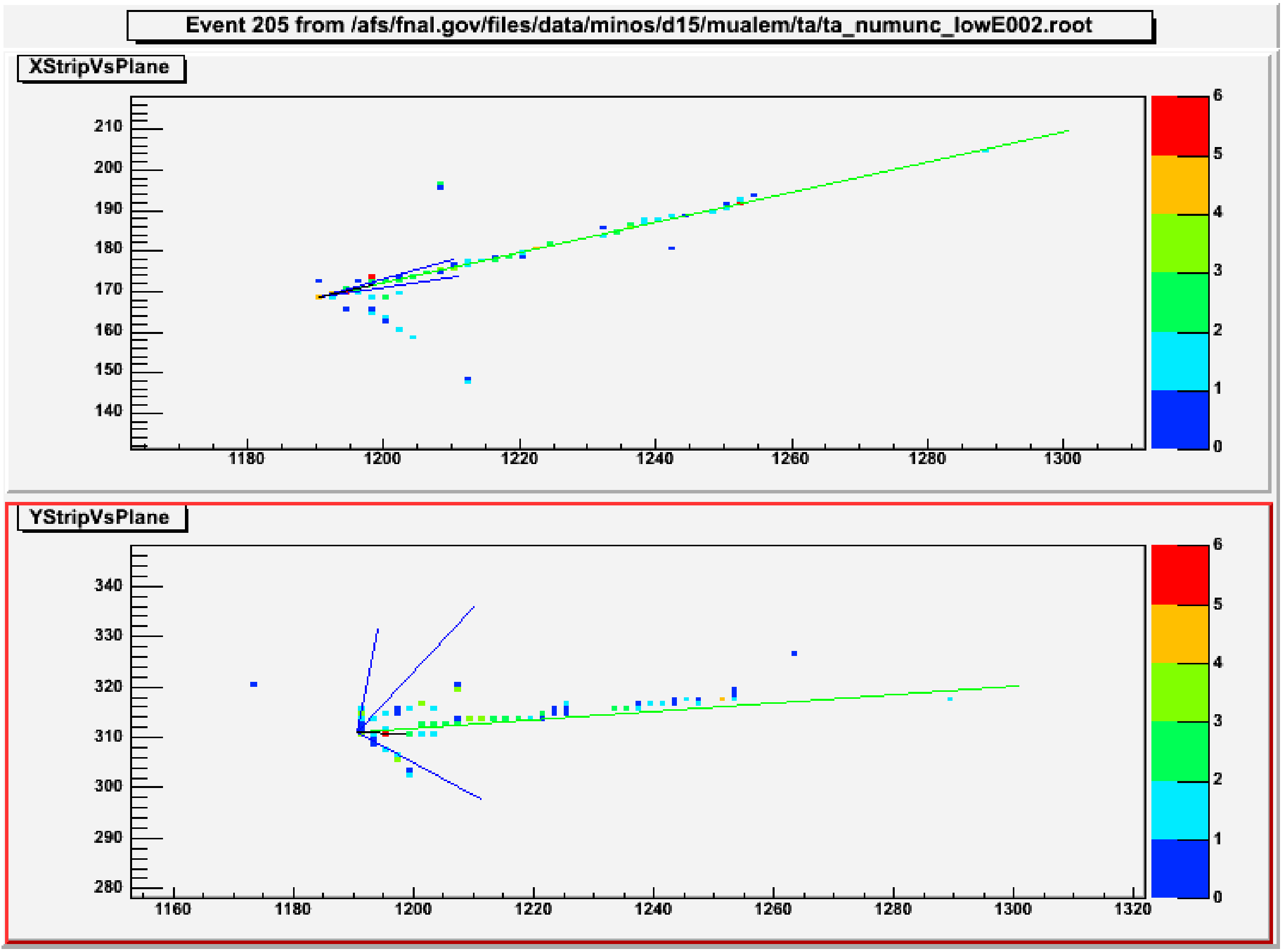
# Event #4

The color code indicates the relative pulse height




The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

# Event #4




The color code indicates the relative pulse height

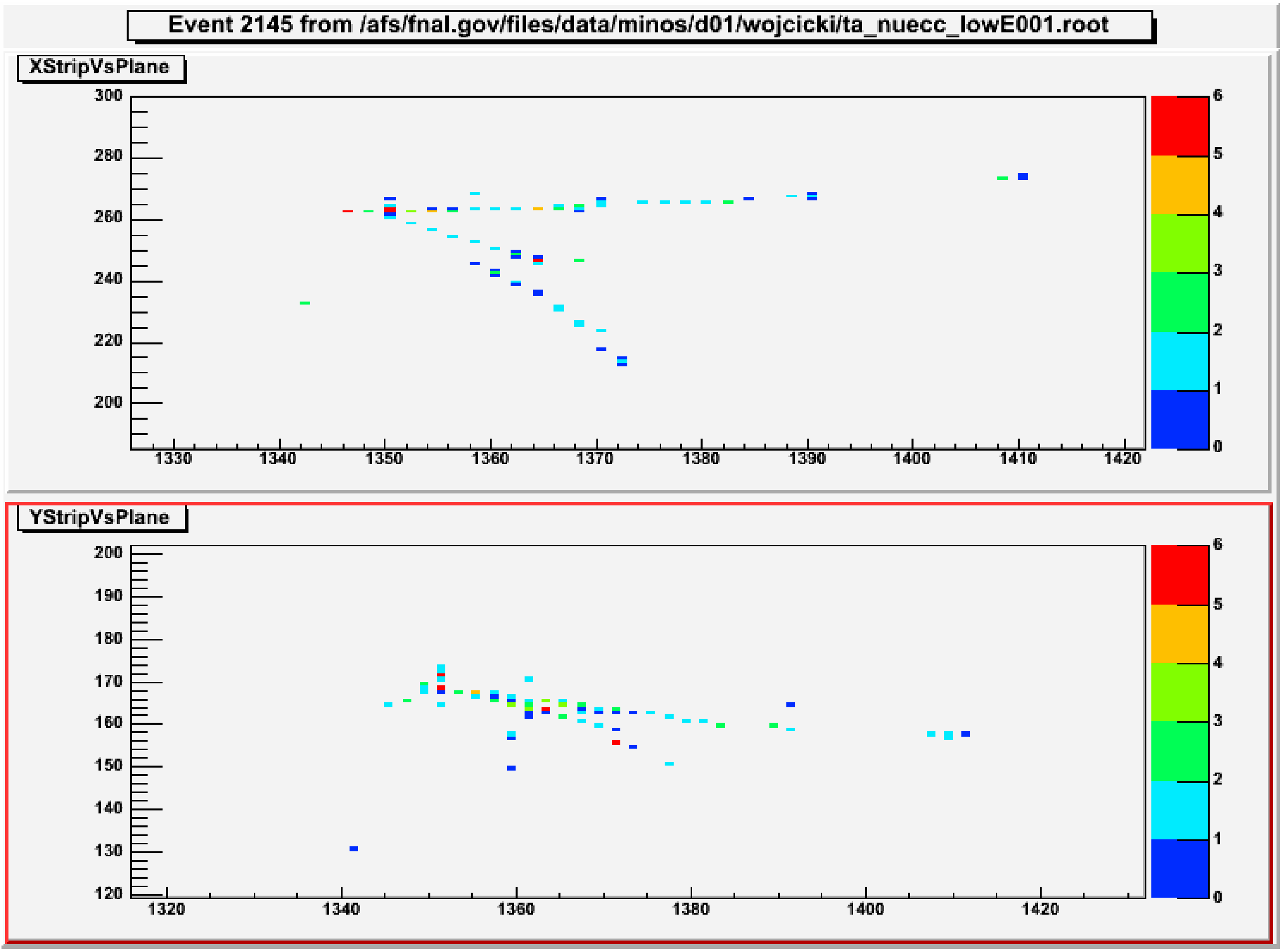
The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

The lines are the trajectories of the final state particles: charged leptons in red, charged pions in blue, protons in black, and neutral pions in green

The line length is proportional to energy, but NOT to the expected path length of the track

A background ν NC event, $\nu + A \to p + \pi^- + \pi^- + \pi^+ + \pi^0 + \nu$, $E_\nu = 4.95$ GeV

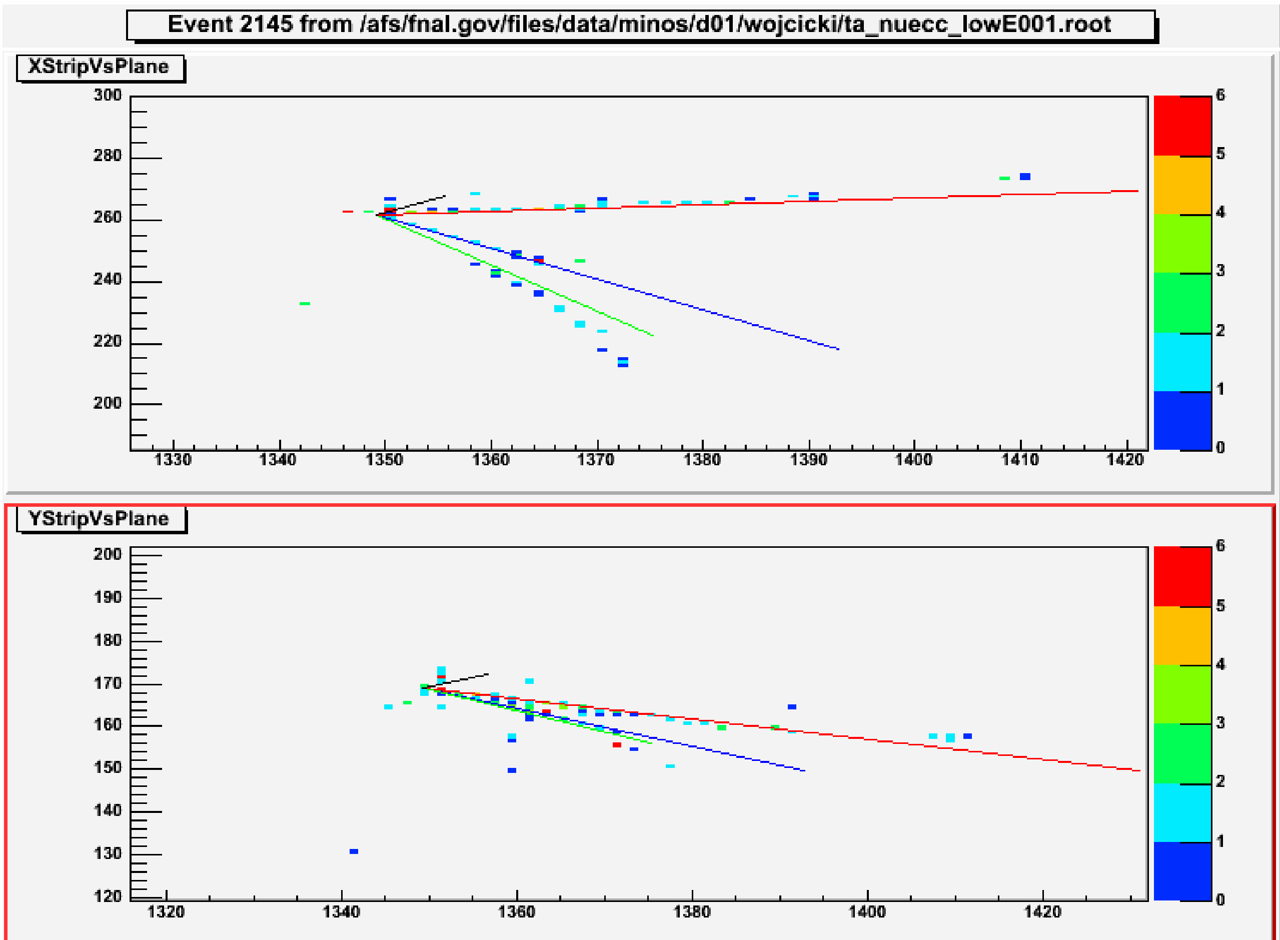
# Event #5




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

# Event #5




The color code indicates the relative pulse height

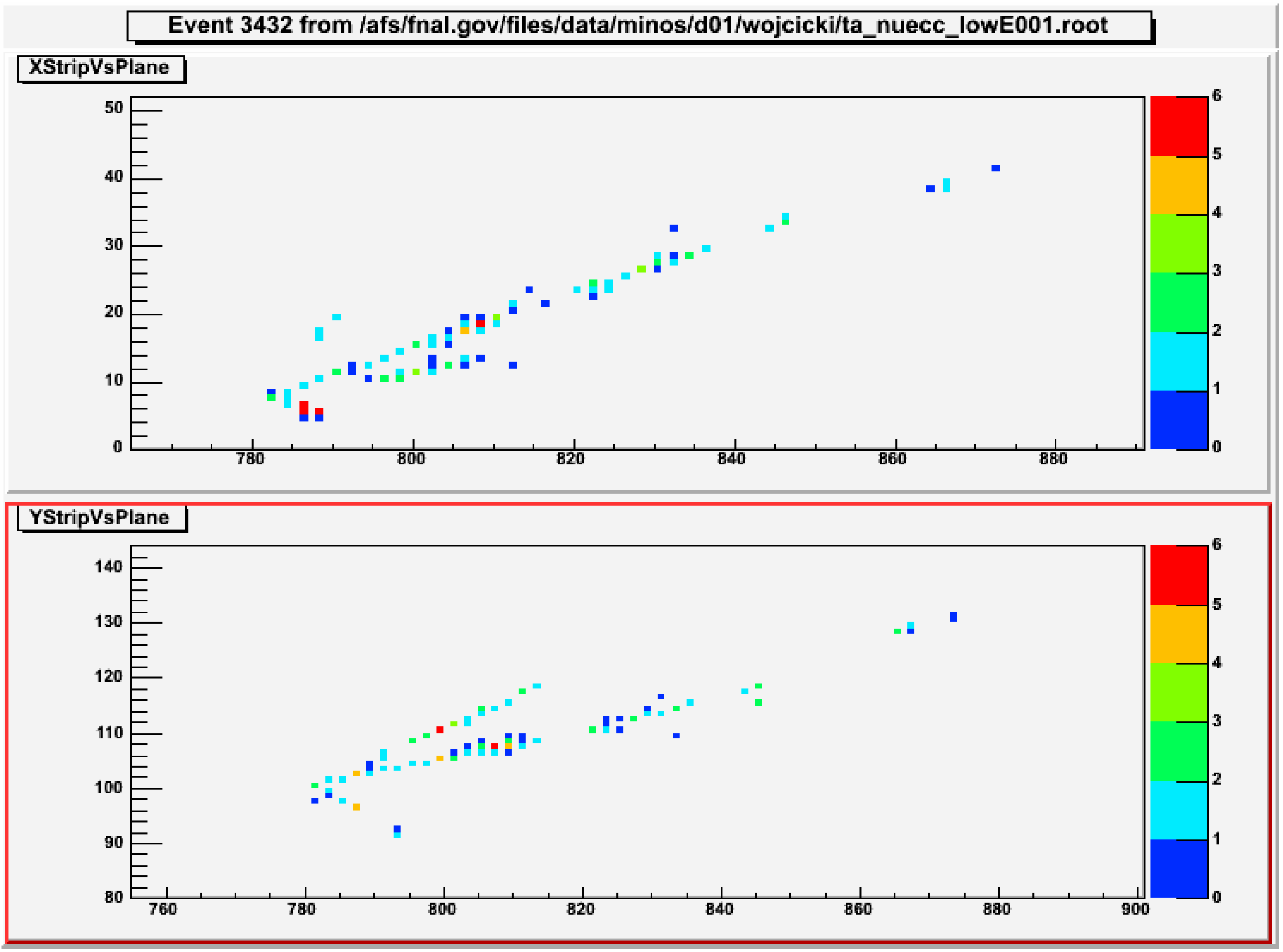
The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

The lines are the trajectories of the final state particles: charged leptons in red, charged pions in blue, protons in black, and neutral pions in green

The line length is proportional to energy, but NOT to the expected path length of the track

A $\nu_e$ CC event     p pi+ pi0 e-   2.53 GeV,     lower (1-y)

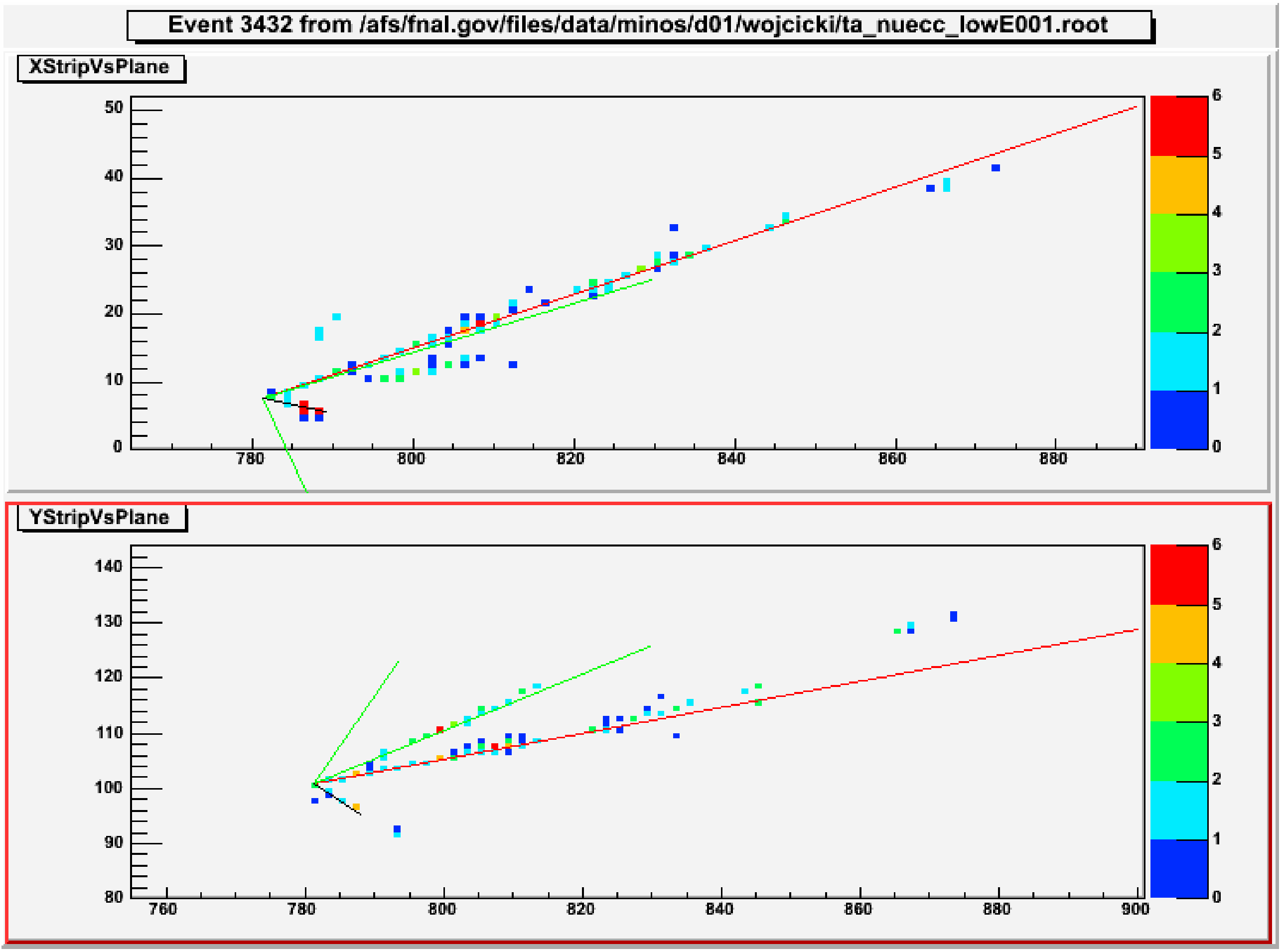
# Event #6




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is
4.9 cm horizontal axis
4.0 cm vertical axis

# Event #6




The color code indicates the relative pulse height

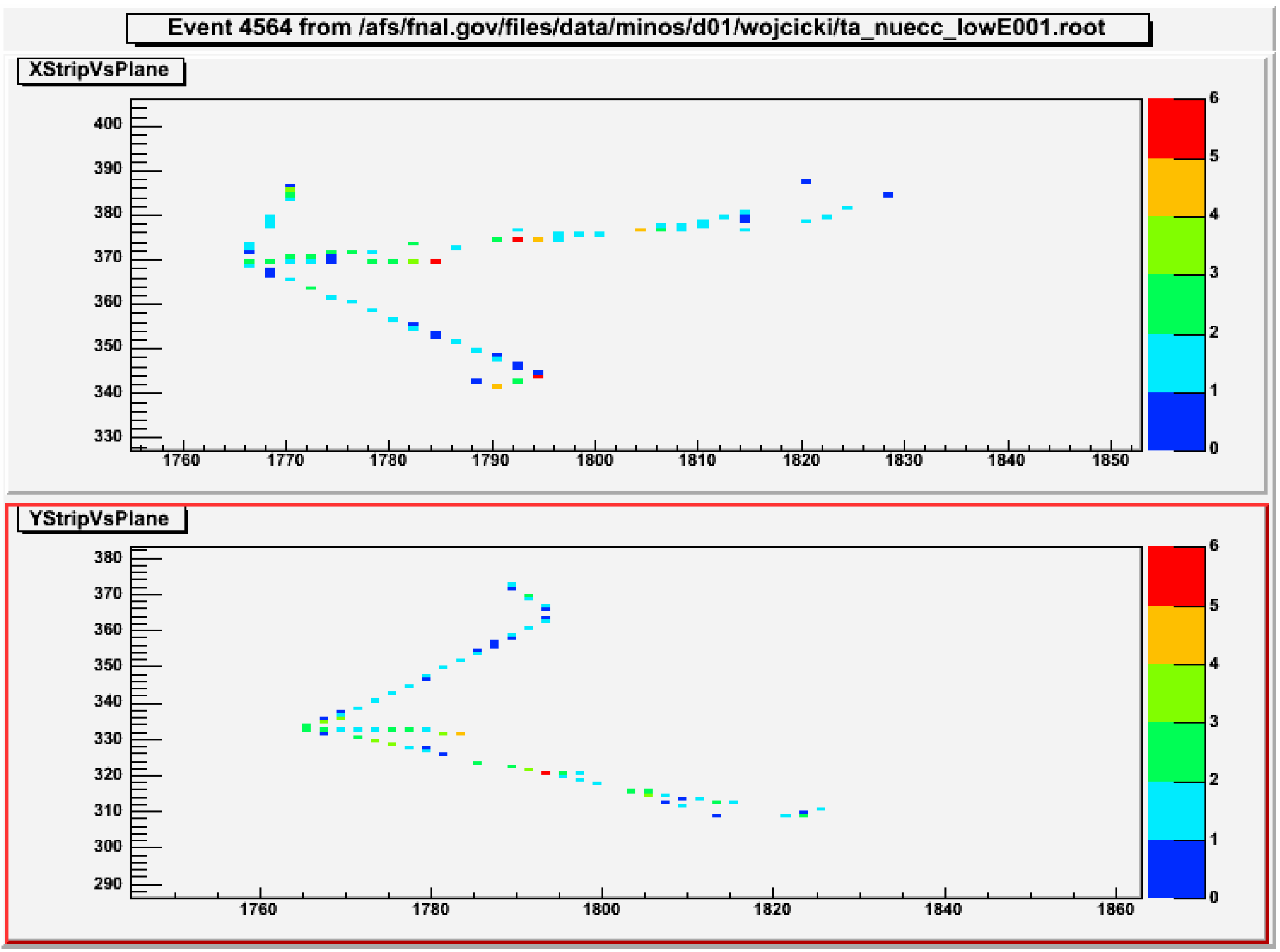
The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

The lines are the trajectories of the final state particles: charged leptons in red, charged pions in blue, protons in black, and neutral pions in green

The line length is proportional to energy, but NOT to the expected path length of the track

A $\nu_e$ CC event p 2 pi0 e- 2.76 GeV, lower (1-y)

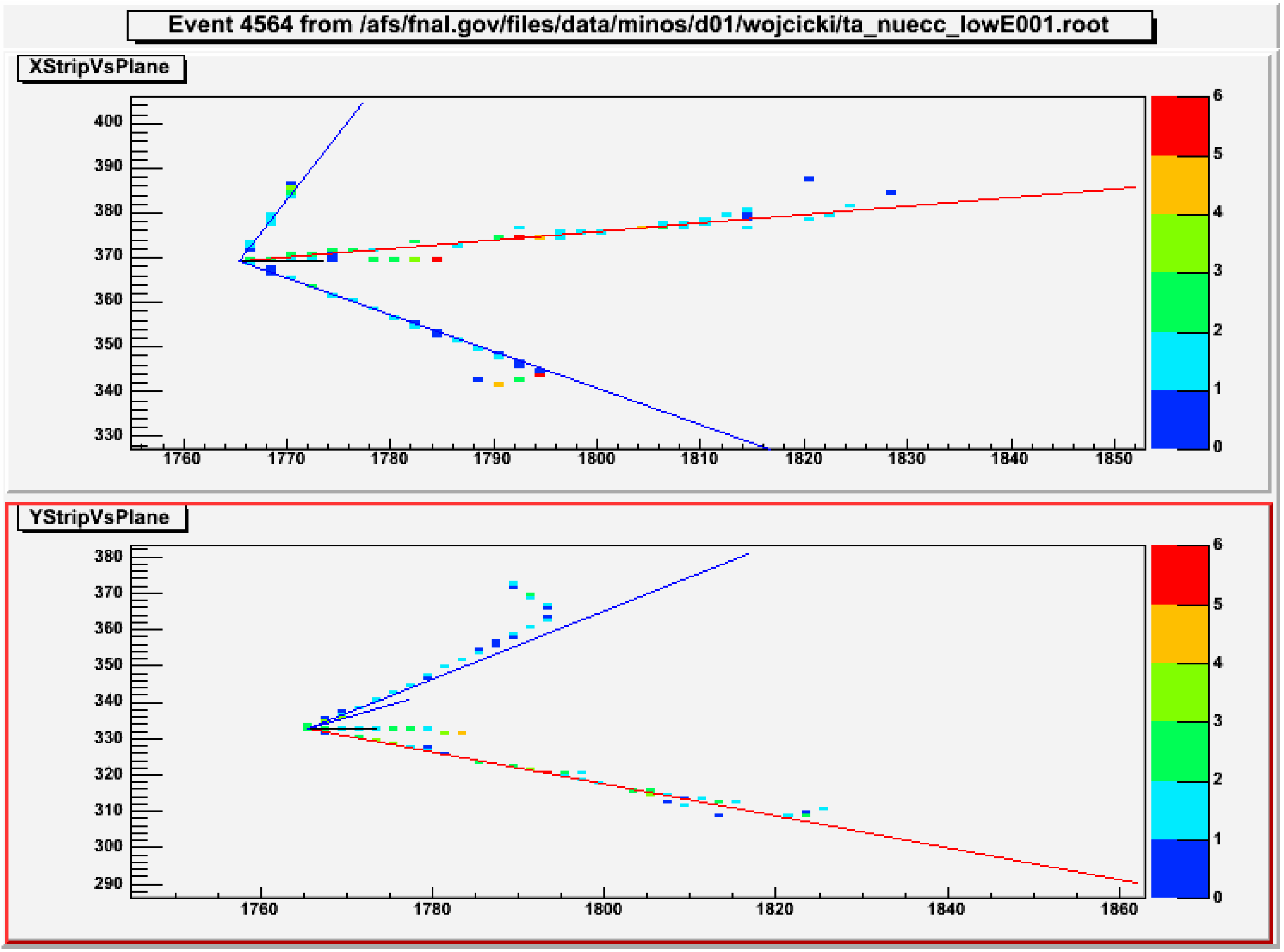
# Event #7




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

# Event #7




The color code indicates the relative pulse height

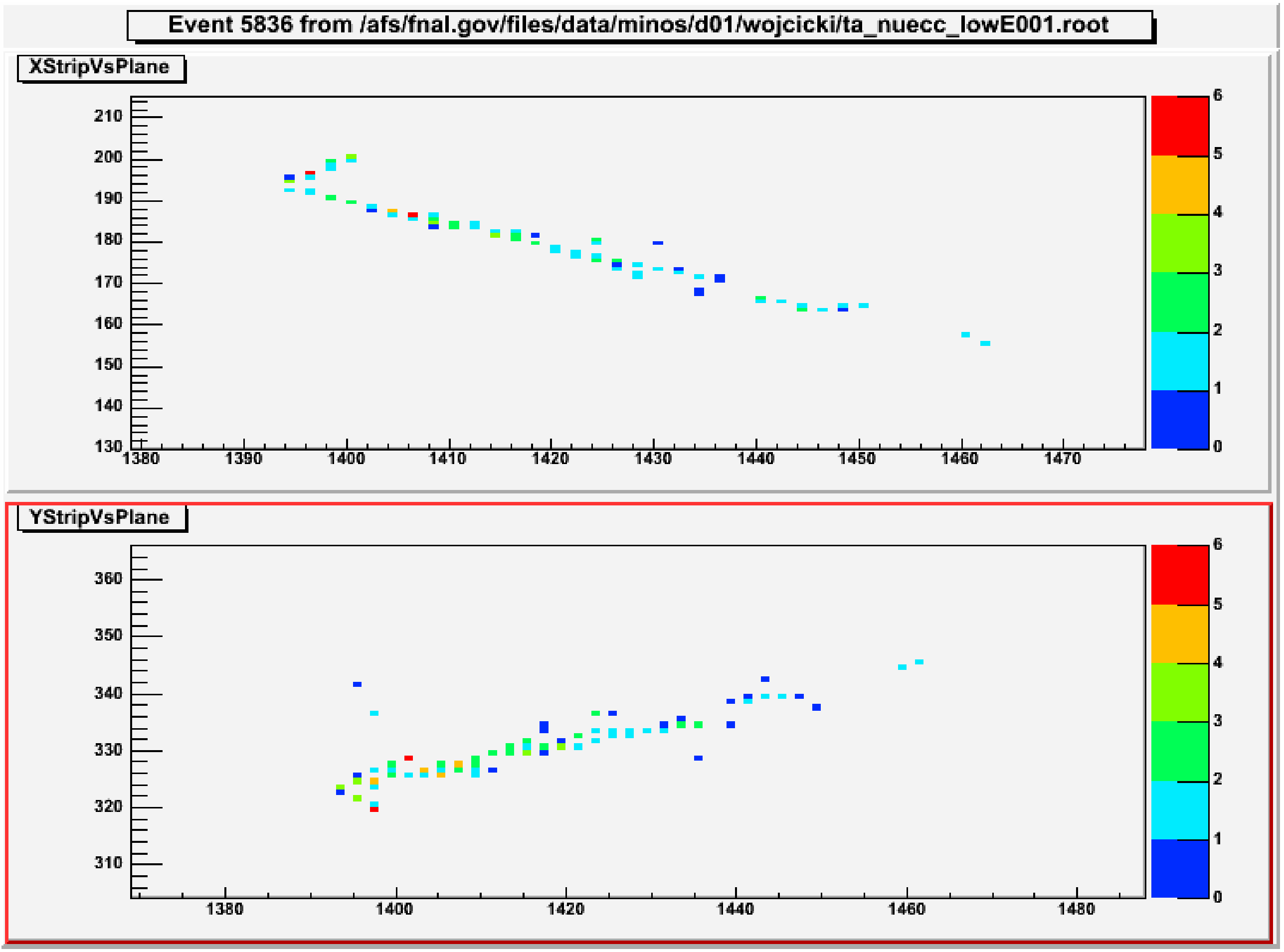
The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

The lines are the trajectories of the final state particles: charged leptons in red, charged pions in blue, protons in black, and neutral pions in green

The line length is proportional to energy, but NOT to the expected path length of the track

A $\nu_e$ CC event p pi+ pi- e- 2.52 GeV, lower (1-y)

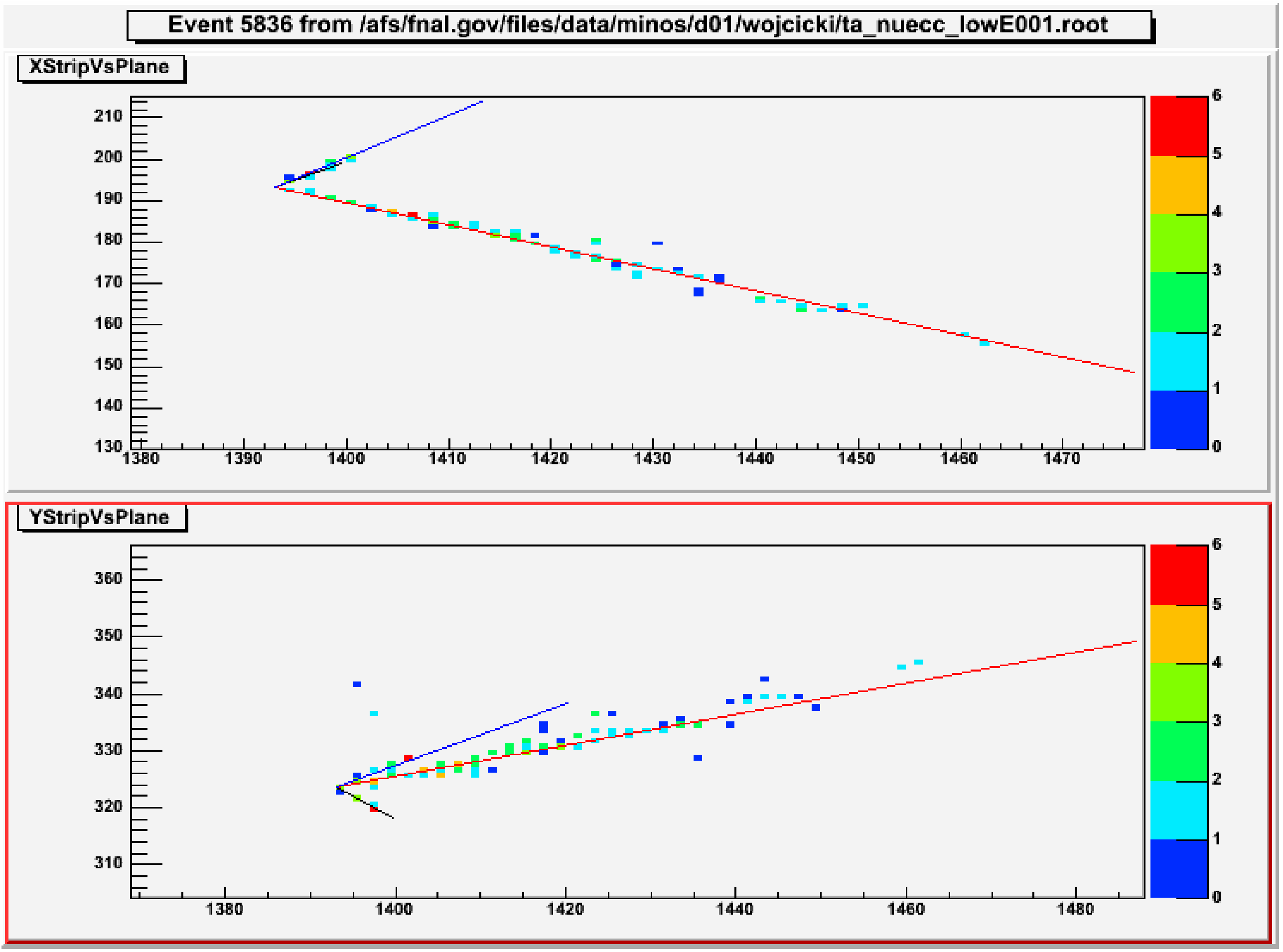
# Event #8




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

# Event #8




The color code indicates the relative pulse height

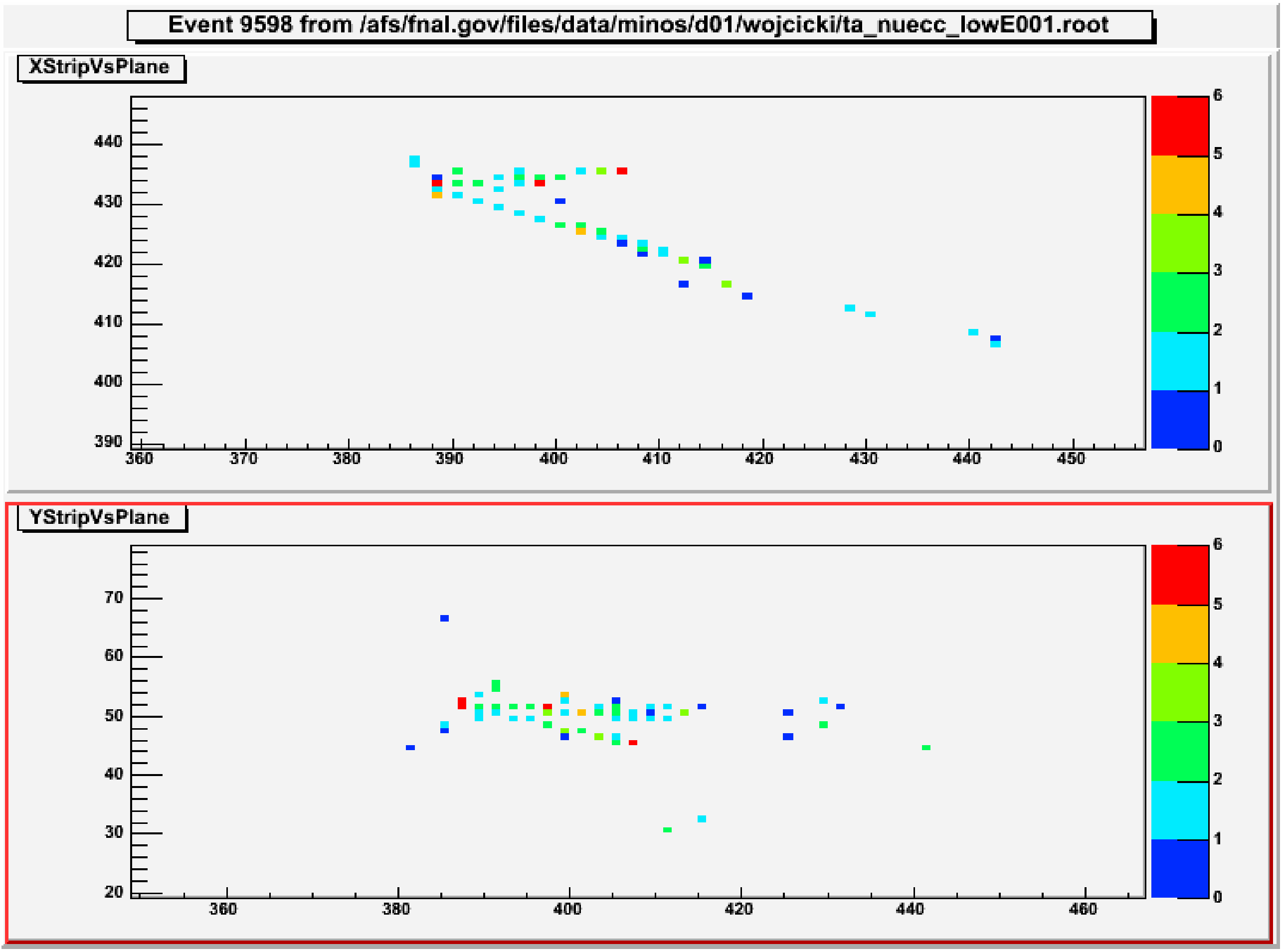
The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

The lines are the trajectories of the final state particles: charged leptons in red, charged pions in blue, protons in black, and neutral pions in green

The line length is proportional to energy, but NOT to the expected path length of the track

A $\nu_e$ CC event p pi+ e- 2.55 GeV

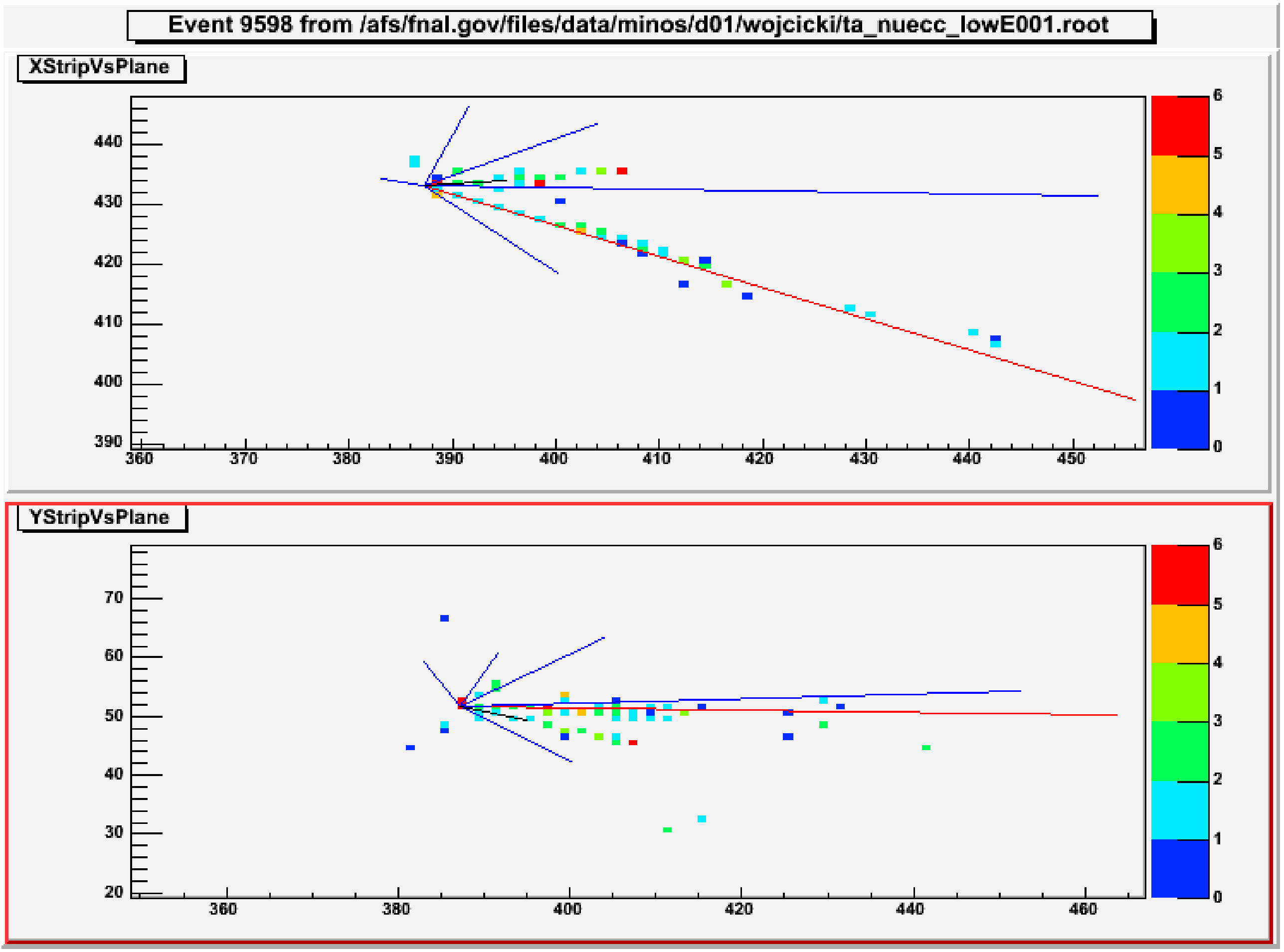
# Event #9




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

# Event #9




The color code indicates the relative pulse height

The scale is in cell numbers, so one unit is 4.9 cm horizontal axis 4.0 cm vertical axis

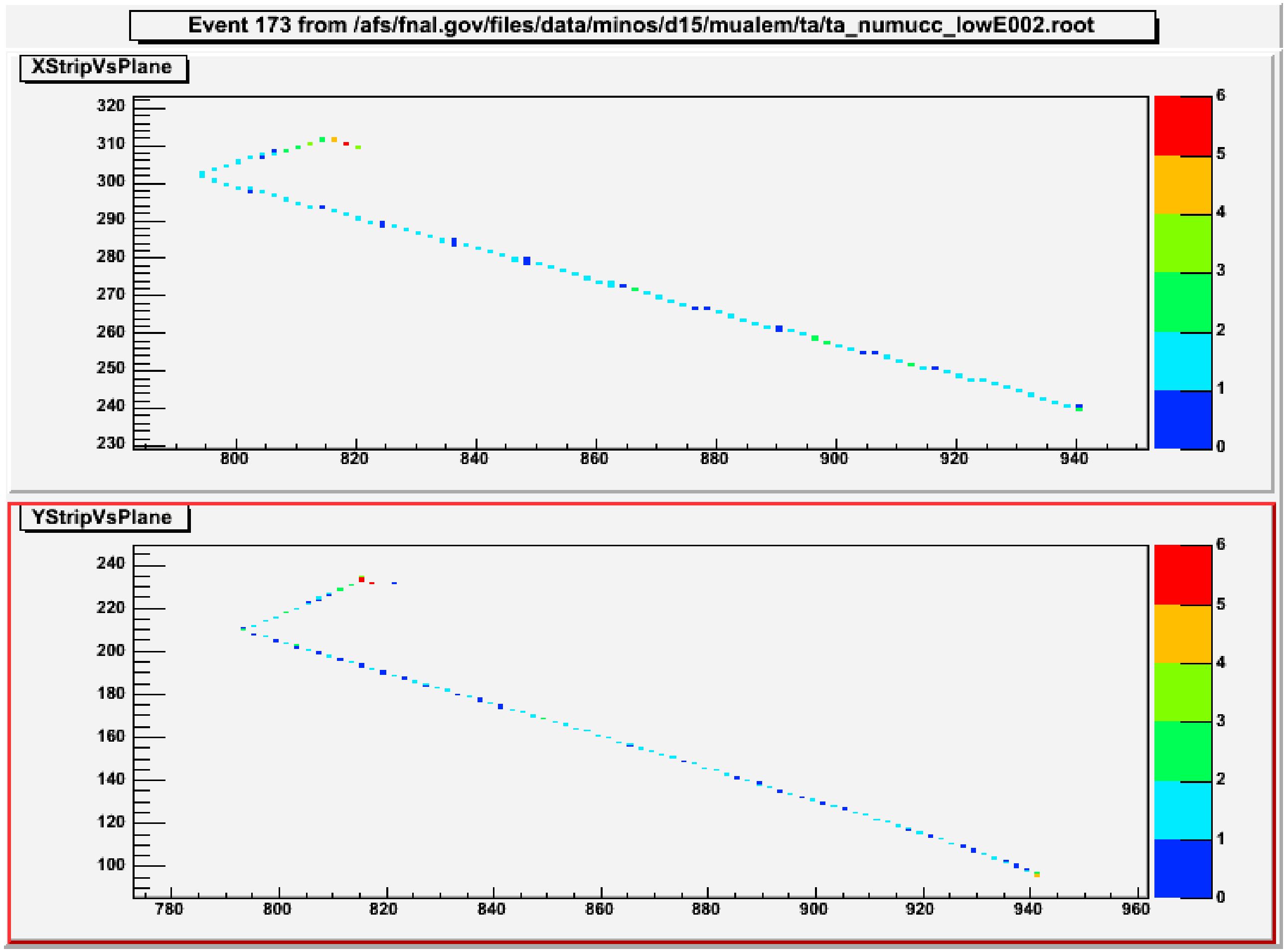
The lines are the trajectories of the final state particles: charged leptons in red, charged pions in blue, protons in black, and neutral pions in green

The line length is proportional to energy, but NOT to the expected path length of the track

A $\nu_e$ CC event p 3pi+ 2pi- e- 2.68 GeV

(pions are very soft ~100 MeV)

# Event #10    Quasielastic $\nu_\mu$




An example of a quasielastic $\nu_\mu$ CC interaction in the TASD detector.
Note proton scatter near the end of its range.